Solid State Aircraft

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OAI

Solid State Aircraft
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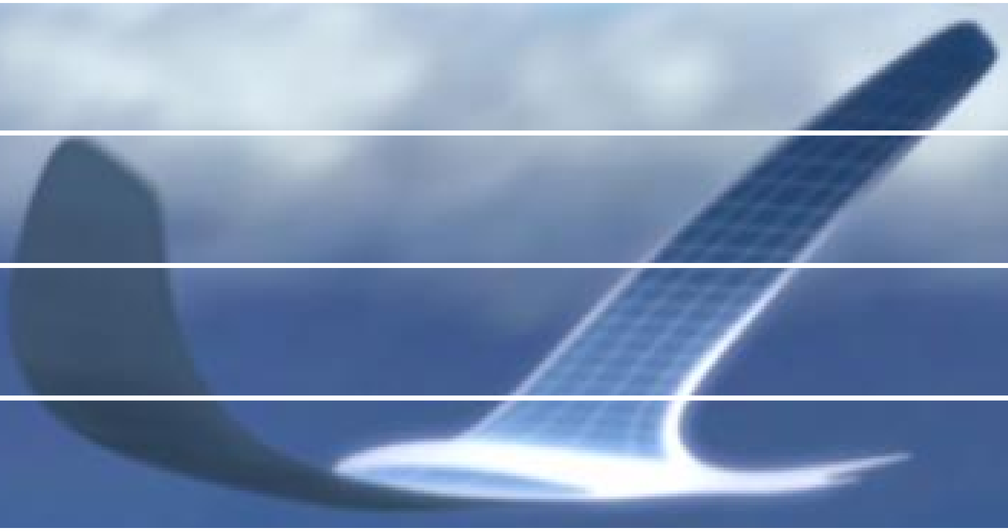
Solid State Aircraft Artist Concept Drawing



The aircraft concept is to integrate three unique types of materials (thin film solar arrays, thin film lithium batteries and an ionic polymer metal composite) to produce an aircraft that has no moving parts, can fly at high altitudes, is easily deployable and has applications on Earth, Venus and Mars

Aircraft Operation

[redacted]

Material

Anode Grid

he aircraft operates by collecting and onverting sun light to electricity hrough a thin film photovoltaic array. his electricity is then stored in a attery.

t specified intervals the energy is ischarge to the anode and cathode rids to set up an electric field about he IPMC (synthetic muscles)material his electric field causes the IPMC to nove thereby causing a flapping notion of the wing.

his flapping motion produces lift and hrust for the aircraft.

he electric field generated by the rids is controllable, therefore the shape and motion of the wing is controllable on each flap.

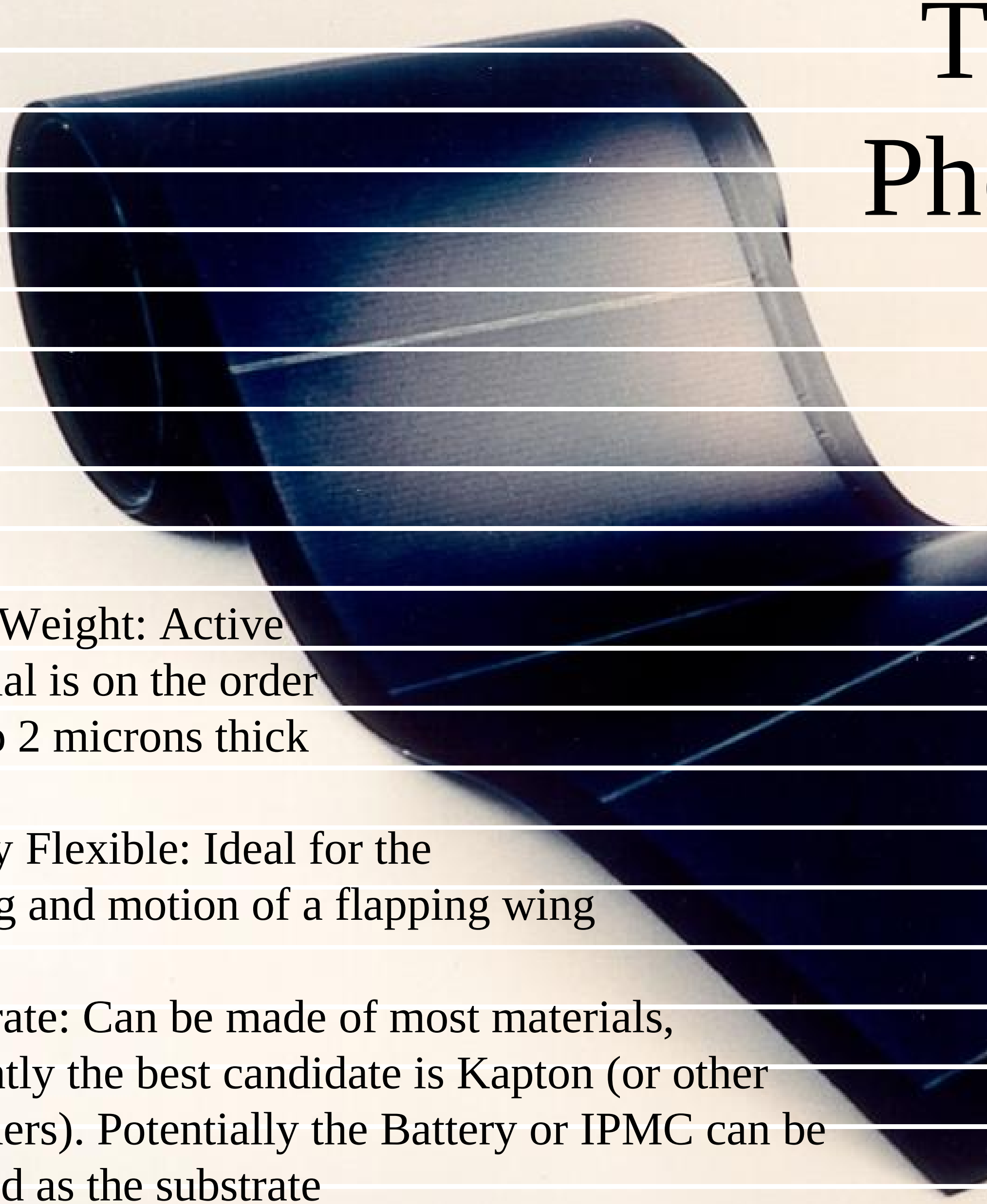
Aircraft Construction & Control

- The unique structure combines airfoil, propulsion, energy production and storage and control.

- To control the motion of the wing a control grid will be used. This grid will enable various voltages to be sent to different sections of the wing, thereby causing varying degrees of motion along the wing surface. The amount of control on the wing will depend on the fineness of this control grid. A central processor will be used to control the potential of each of the sections.

- This control enables the wing to fla[redacted] provide differential lift (which is u[redacted] for steering), and alter the camber [redacted] of the wing to maximize lift under a given operational conditio[redacted]

Thin Film Photovoltaic Array

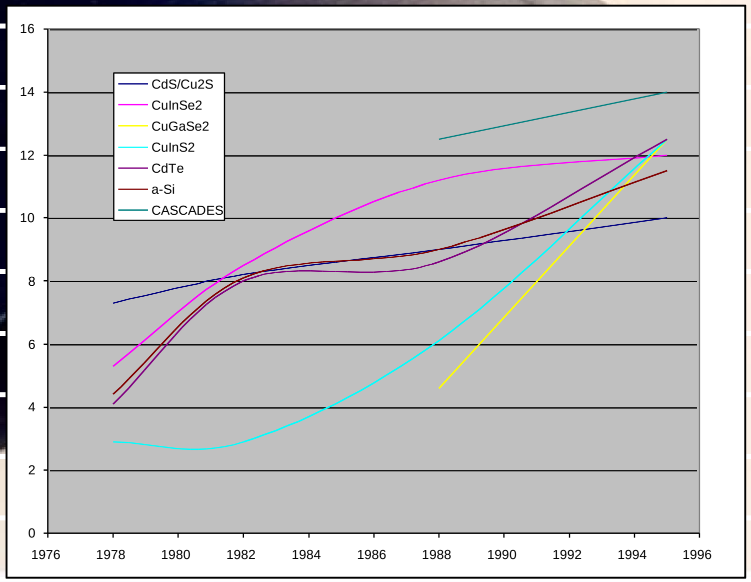


Light Weight: Active material is on the order of 1 to 2 microns thick

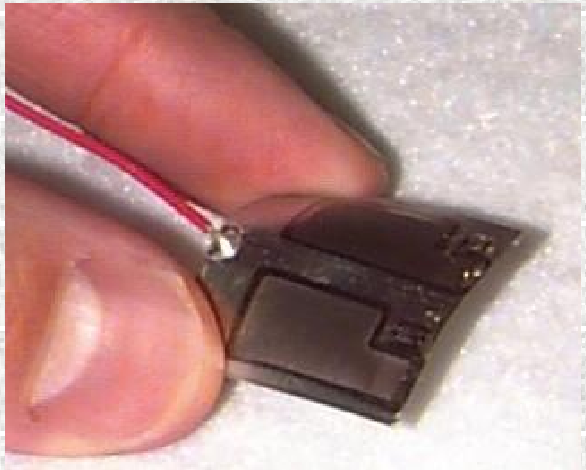
Highly Flexible: Ideal for the flexing and motion of a flapping wing

Substrate: Can be made of most materials, presently the best candidate is Kapton (or other polymers). Potentially the Battery or IPMC can be utilized as the substrate

Specific Power: 1 kW/kg near term, 2 kW/kg projected



Thin Film Battery/Capacitor Characteristics



ITNES sample battery

- Rechargeable, Lightweight and Flexible
- Configurable in any series / parallel combination
- Rapid charging / discharging capability
- Can be charged / discharged 1000s of times with little loss in capacity
  - Enables long duration flight times

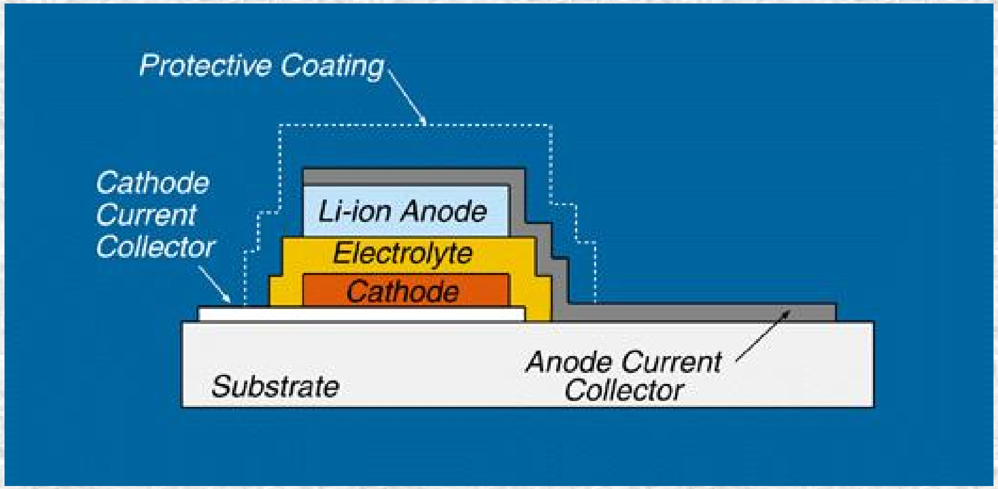
- Long shelf life with little self discharge
  - Ideal for stowage during interplanetary transit
- Operate over a wide temperature range
  - Enables the batteries to operate under various environmental conditions
- The batteries have the capability to provide high pulse currents
  - Ideal for short duration power loading such as flapping the wings

Battery Construction & Operation

Types of Lithium ion thin-film batteries differ in the cathode material they use.

– Ex. Magnesium Oxides, Cobalt Oxides, Yttrium Oxide

The battery is produced by depositing (through sputtering or evaporation techniques) the various material layers that make up the components (cathode, electrolyte, anode and current collector) onto a substrate.



Oak Ridge Battery Design Cross Section (15 micron thick)

Ionic Polymer-Metal Composite (IPMC)

QuickTime™ and a
decompressor
are needed to see this picture.

- This is the core material of the aircraft. It provides the propulsion and control for the vehicle.
- The IPMC material has the unique capability to deform when an electric field is present across it. The amount and force of the deformation is directly related to the strength of the electric field.
- The deformation is not permanent and returns to its original shape once the electric field is eliminated.
- The material can be manufactured in any size and initial or base shape.

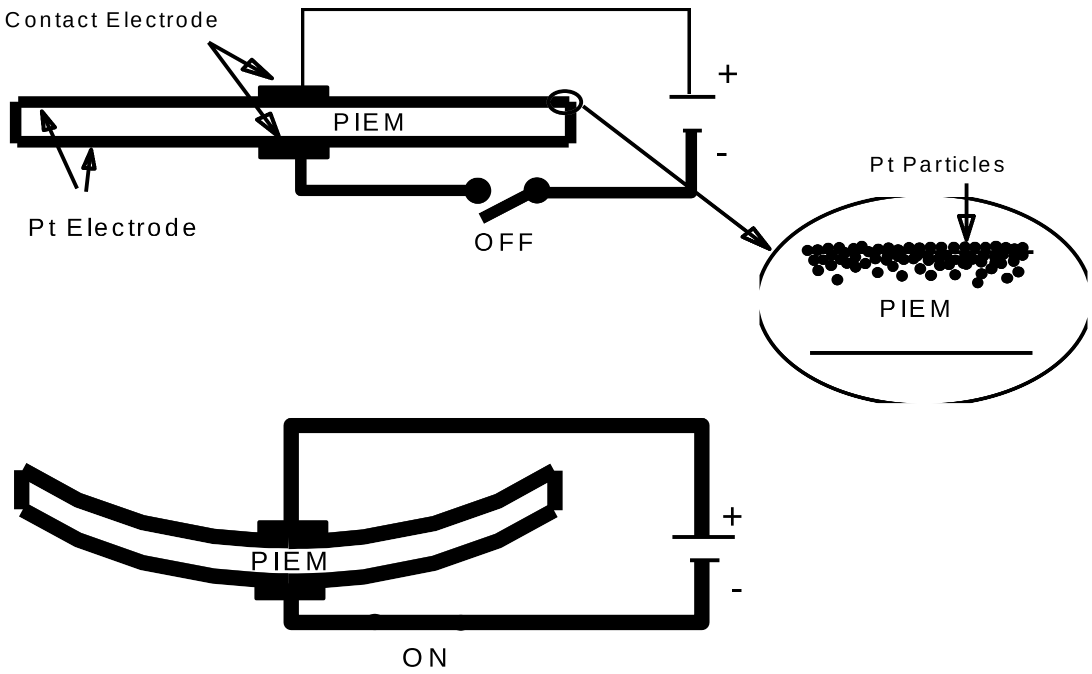
IPMC Material

Constructed of an Ion Exchange Membrane that is surface coated with a conductive medium such as Platinum

Placement of the electrodes can be used to tailor the bending of the material to any shape

Metal Electrodes

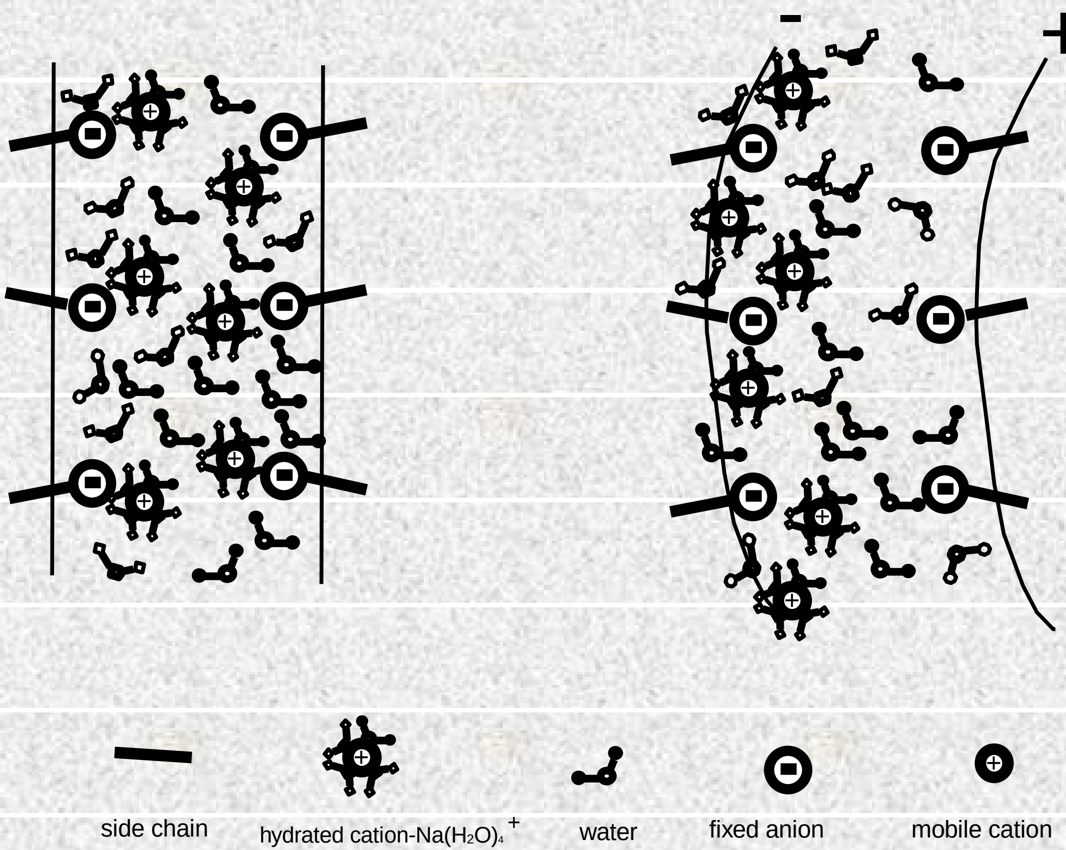
The material will bend toward the anode side of the electrodes



IPMC Motion

Under an electric field the ion exchange membrane
Enables the migration of ions which allows water molecules and
Hydrated cations to migrate toward the negative pole.

This internal movement of water molecules is responsible for creating
Internal strains within the material which enable it to move



For the IPMC material to operate it must be sufficiently Hydrated

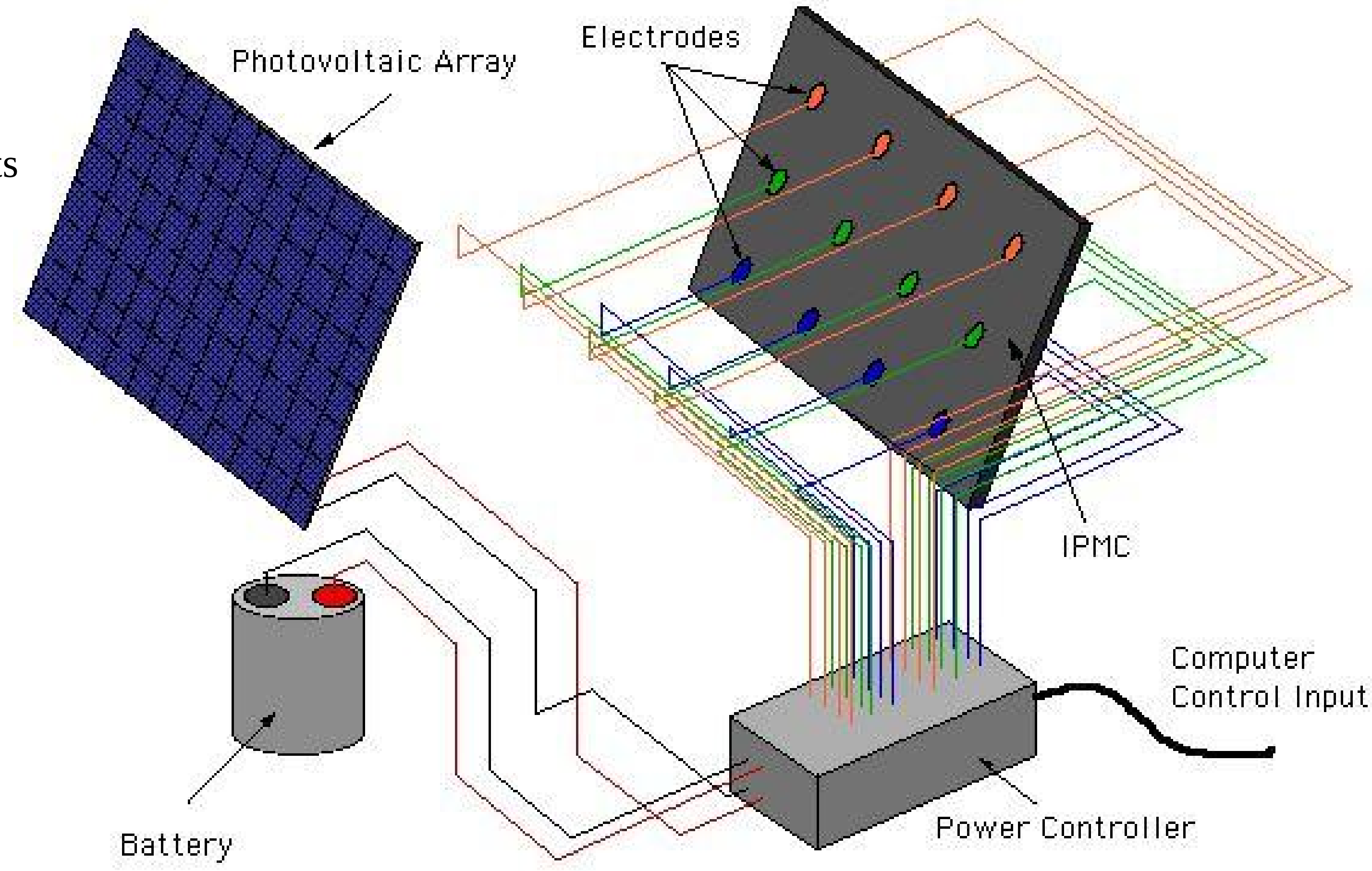
Leakage and operation in dry environments may require sealing or redesign of the material for efficient long term use

IPMC Material Characteristics

Material Integration: Near Term

Goal: To produce a method for combining the solar array, battery and IPMC materials into a single flexible structure for lab testing.

- •Off-the-Shelf components will be used as much as possible.
- •The array & IPMC will be assembled using adhesives, lamination or other readily available means.
- •The control grid will be constructed integral with the IPMC material.
- •Potential adhesion methods will be tested on coupon samples of the thin film array, IPMC, wiring and electrodes.
- •Due to the development stage of thin film batteries, these initial integration tests will only include the array and IPMC materials.
- •External batteries or capacitors will be used during this initial testing.
- •The various integration methods will be tested for adhesion and bending capability.



Long Term Integration Strategy

Goal: To provide a scheme to producing a fully integrated composite structure from the three main materials and subsequent components.

• The potential of construction the SSA by depositing each component material layer onto the subsequent layer is being investigated.

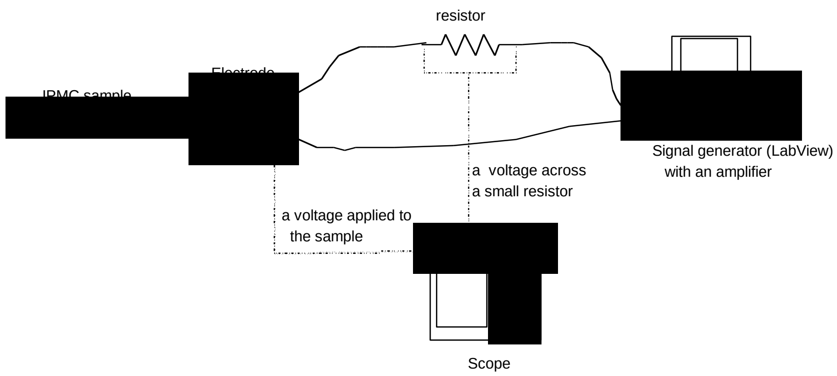
•This method would use the IPMC material as the main substrate.

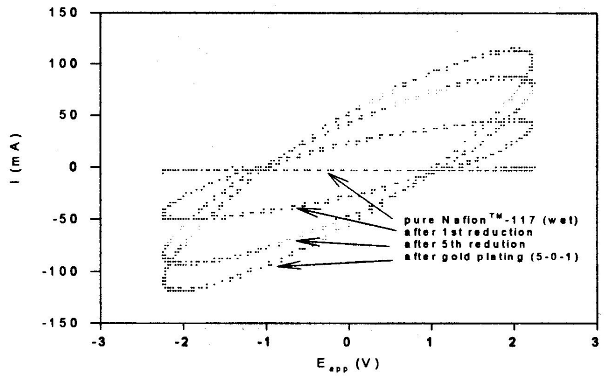
•The battery layer and solar cell layer as well as the electrodes and wiring would be build directly onto the IPMC through a combination of deposition and lithography techniques.

•Some of the main issues that are to be examined are the material compatibilities, adhesion characteristics, material thickness and deposition and lithography techniques, their capabilities and requirements.

Wing Control

•The placement of electrodes and the shape of the electric field they generate dictates the wing motion





The Current-Voltage Response to Sine Voltages of 2.2 V

Nafion™-117 (Pt), #051199
E_{app}=2.2 volts (LabView scale~1.2), 1/2 Hz,
Air contact, L=2", W=1/2"

Schematic Design of the I-V Measurement Set-Up

Electrode Placement & Operation

This is one of the more critical & challenging tasks to be undertaken

- For efficient flight the wing must be capable of flapping, twisting & changing the camber of the airfoil along the wing length
- This is accomplished by the placement and operation of the electrodes that control the IPMC material motion

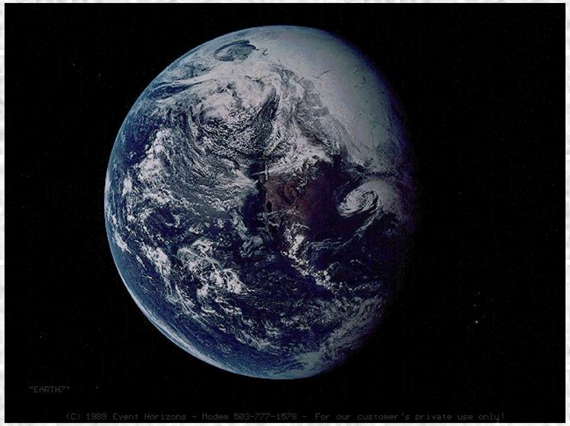
Analysis of the electric field generation for various electrode placements

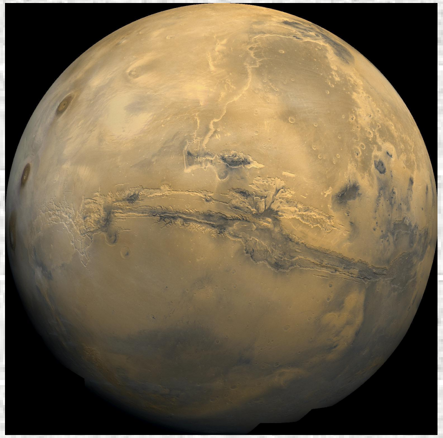
Devise an electrode layout & associated voltage strength / polarity to achieve a given wing shape

Devise a means of controlling electrode voltage from a single processor & power source

Produce a wing test section to validate the electric field analysis & control scheme

Solid State Aircraft Applications



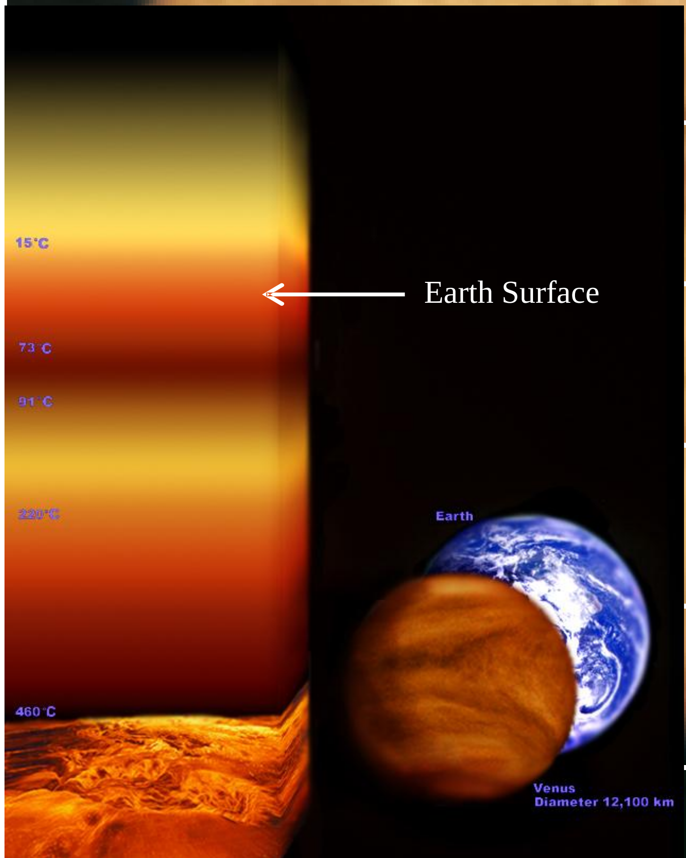


There is sufficient solar intensity for this aircraft to operate on Earth, Venus or Mars

Because of its projected relatively small mass and flexibility, the aircraft is ideal for planetary exploration. These characteristics allow the aircraft to be easily stowed and launched at a minimal cost. Potentially, a fleet of these aircraft could be deployed within a planet's atmosphere and used for comprehensive scientific data gathering, as an quickly deployable quiet observation platform or as a communications platforms.

Venus Environment

• **Rotation Period (Day) of Venus is Longer the Revolution Period (Year) Potentially Enabling Continuous Flight**



• **Atmosphere is mainly Carbon Dioxide (96.5%) Also contains trace amounts of corrosive Compounds (Hydrochloric, hydrofluoric & Sulfuric Acids)**

• **Atmospheric Density Equals Earth Surface Density at ~50 km**

• **Incident Solar Intensity is ~2600 W/m^2**

• **Very high wind speeds above the cloud tops ~ 100 m/s**

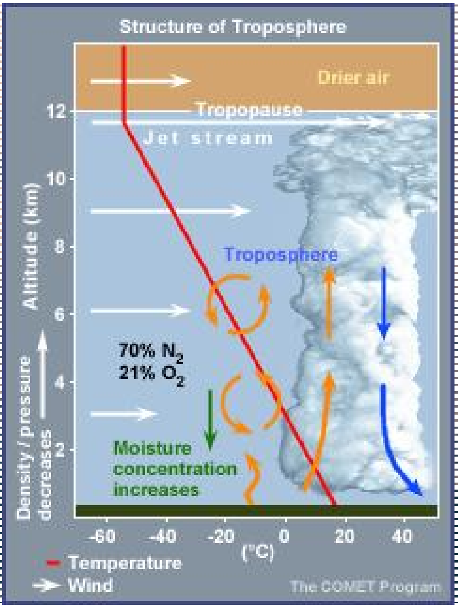
• **Clouds On Venus Extend Upwards to ~64 km**

Earth Environment

- Gravitational Force 9.81 m/s^2
- Solar Intensity 1352 W/m^2
- Atmospheric composition is approximately 80% Nitrogen, 20% Oxygen

Wind speeds generally increase from the surface up to a maximum around the top of the Troposphere (Jet Stream)

The majority of Earth's weather occurs within the Troposphere which extends to approximately 12 km



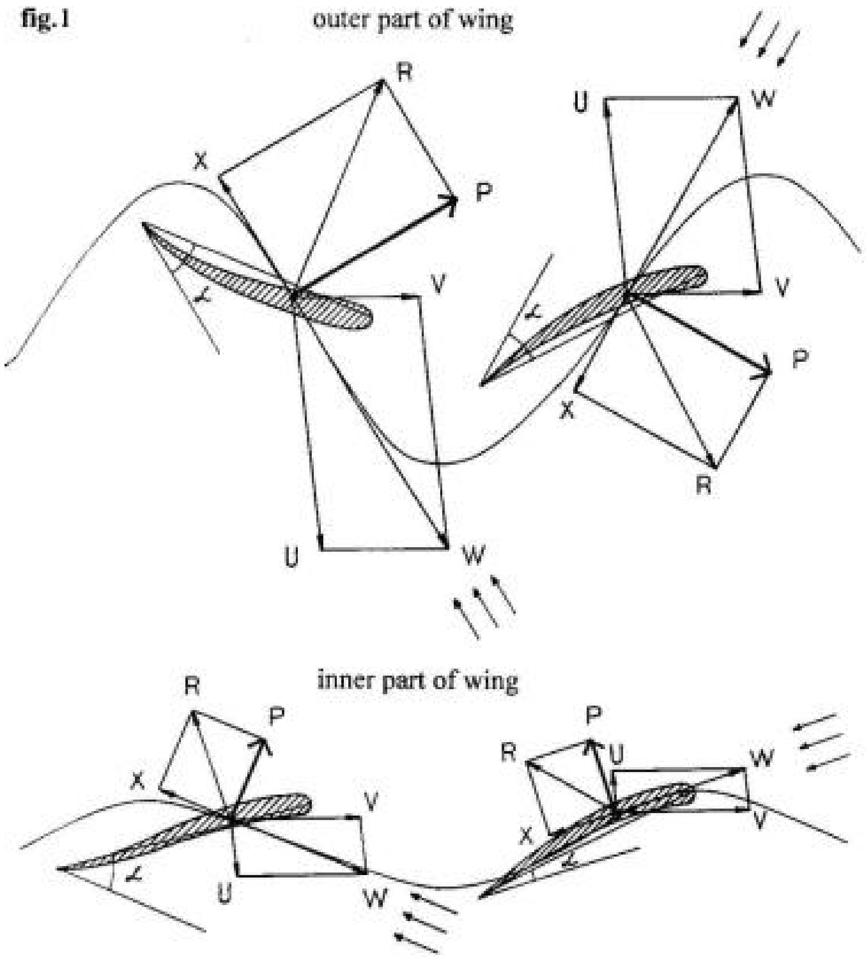
Mars Environment

- The atmosphere on Mars is very thin. At the Surface the density is similar to 30 km on Earth
- The atmosphere is composed mostly of Carbon Dioxide

- The temperature on Mars is on average much colder then on Earth Although at certain times of the year and locations the temperature will rise above freezing, most of the time temperatures are well below the freezing point of water.
- The gravitational force on Mars ($3.57\ m/s^2$)is about 1/3 what it is on Earth.
- Solar intensity at Mars is ~590 W/m^2
- There are few clouds but dust storms are fairly common

Lift and Thrust Generation

The propulsion force and lift generation of the aircraft are accomplished by the flapping of the wings.



By altering the shape and angle of attack of the wing the amount of lift and the direction of this lift force can be controlled

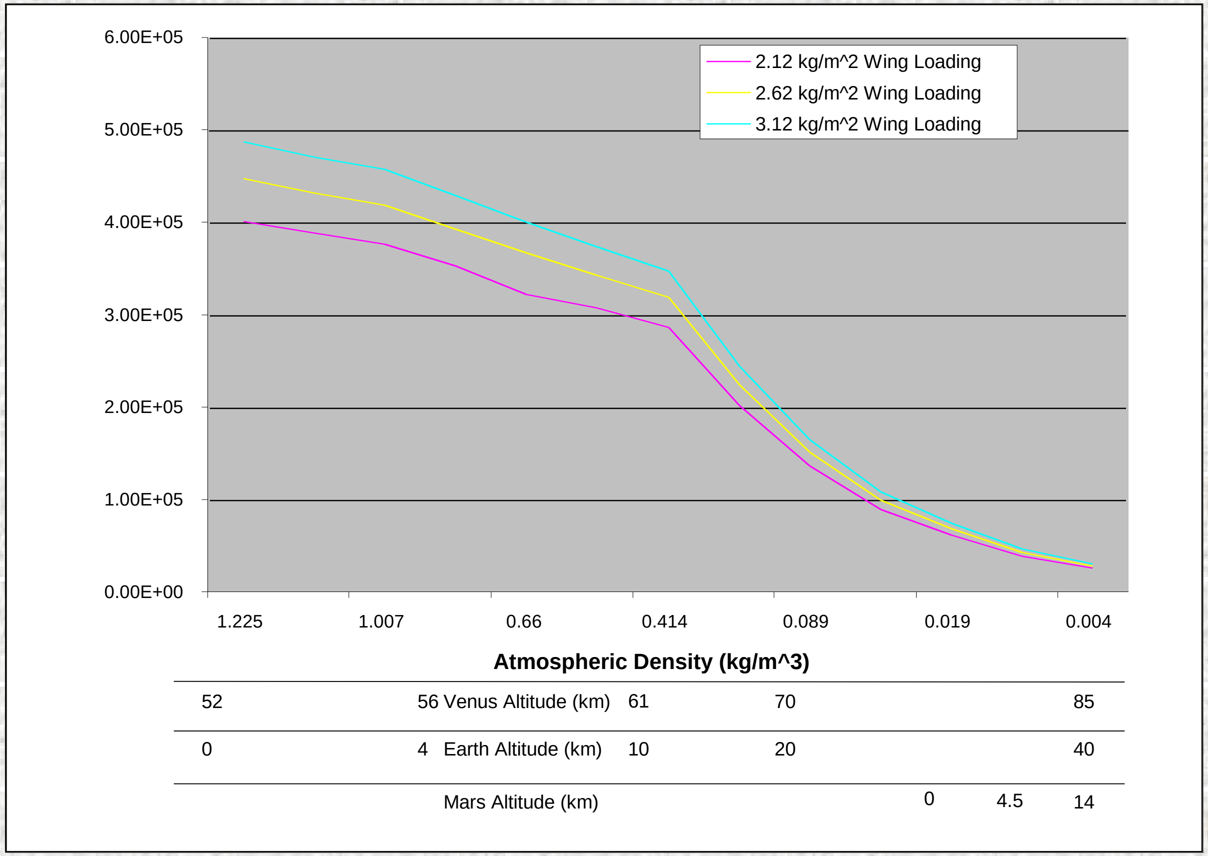
This is the same method birds use to generate lift and thrust

The lift and lift vector generated can Vary between each wing as well as along the wing span itself.

This provides a significant amount of control and provides a means for maneuvering

Wing Aerodynamics

Like all flapping wing flyers in nature the solid state aircraft will operate within a low Reynolds number flight regime. This is due mainly to its required low wing loading and the potential for high altitude operation, where the air density is low.



$$R_e = \frac{Vc}{\mu}$$

Wing Assumptions:

Curved flat plate airfoil
Rectangular wing planform

These are conservative estimates. Wing and aircraft performance can be increased by optimizing the wing design for a specific flight regime.

Ongoing Aerodynamic Analysis & Design

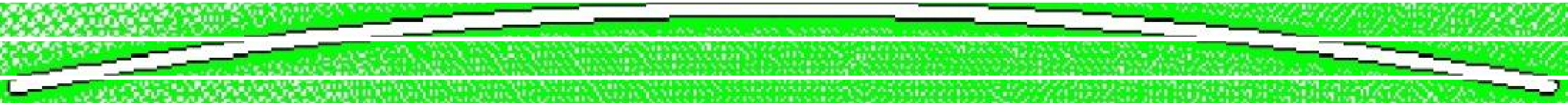
Airfoil Selection: Curved flat plat with 1% thickness & 5% Camber

Attributes: Good low Reynolds number characteristics

Thin cross section minimizes mass

Performance data is available at low Reynolds numbers

2-D performance estimates will be generated under specific flight conditions using airfoil analysis tools (FLUENT, XFOIL)



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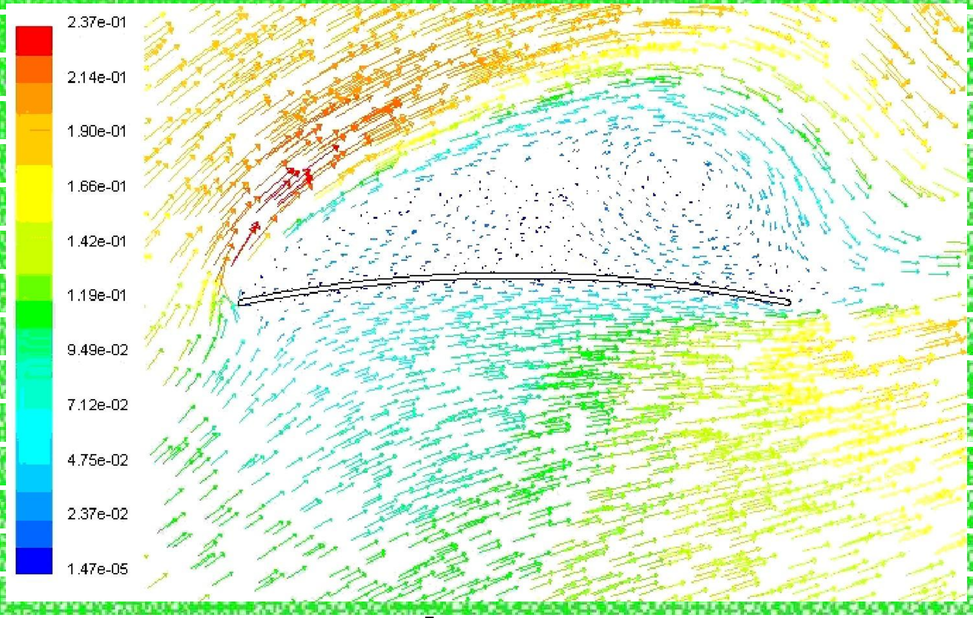
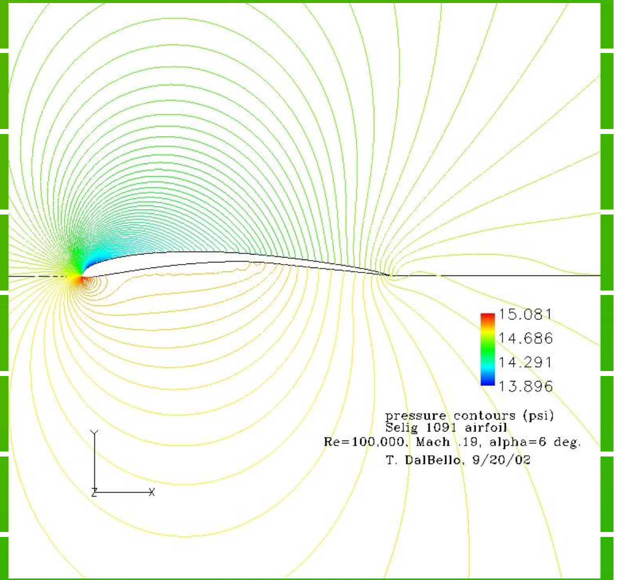


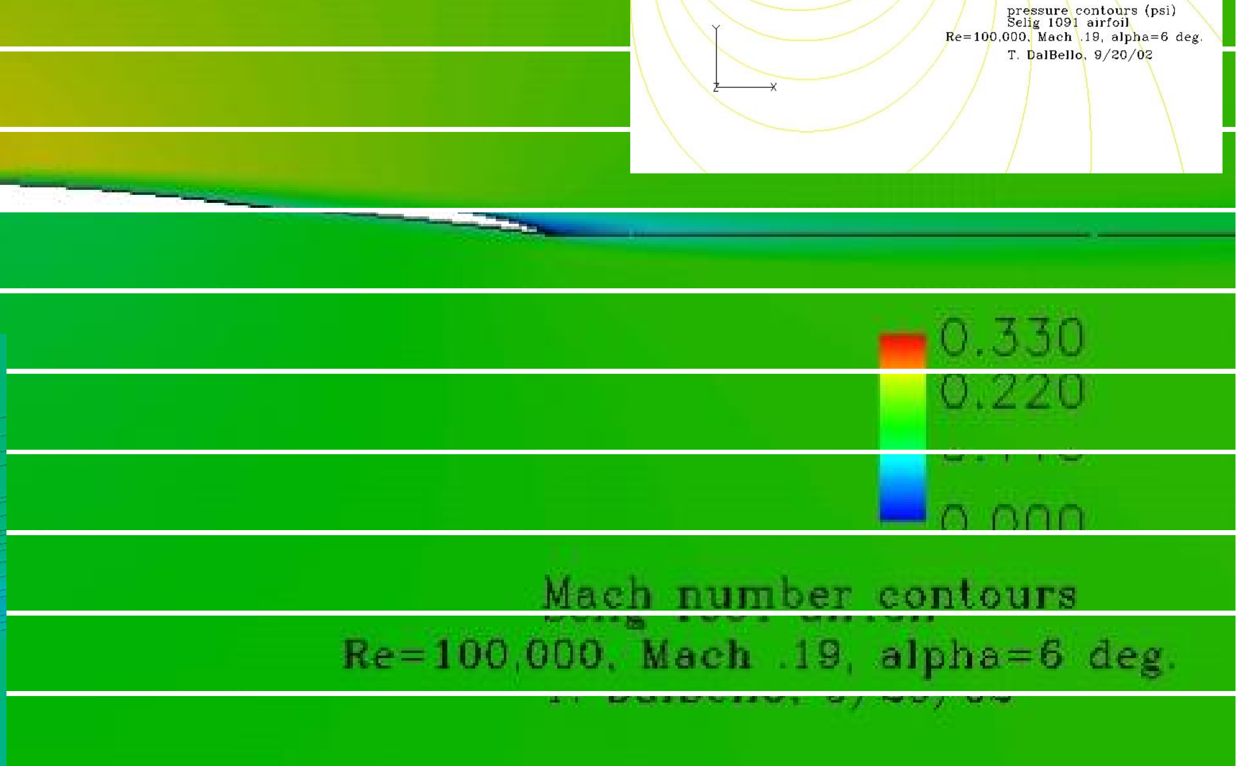
Pressure

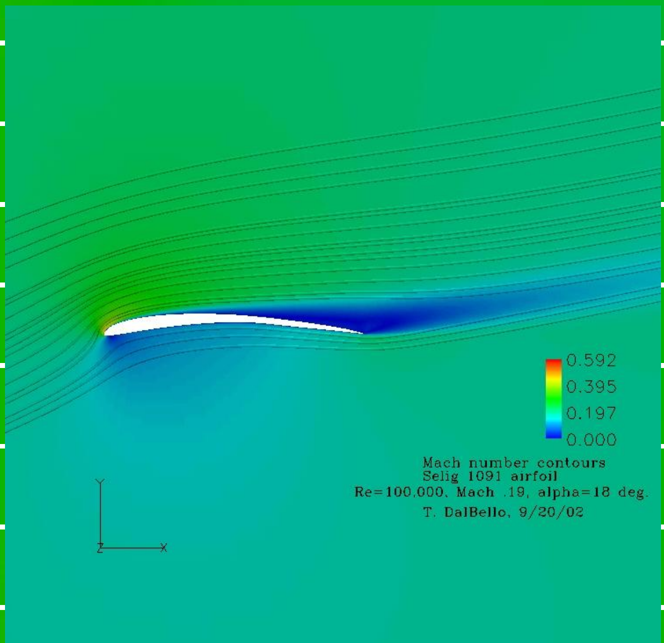
Velocity

CFD Airfoil Analysis

CFD analysis is ongoing to provide lift coefficient and drag coefficient data for a thin curved airfoil at Angles of attack and Reynolds numbers representative Of the estimated SSA flight regime and wing motion







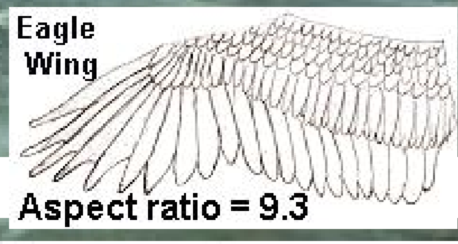
Nature Inspired Configuration

Nature Has A Way Of Finding The Optimum

- The Pteranodon is the largest animal that ever flew.
- It is the closest in size, weight and wing span to the SSA
- As an initial starting point for a more detailed wing design the Pteranodon wing shape will be used as the model.

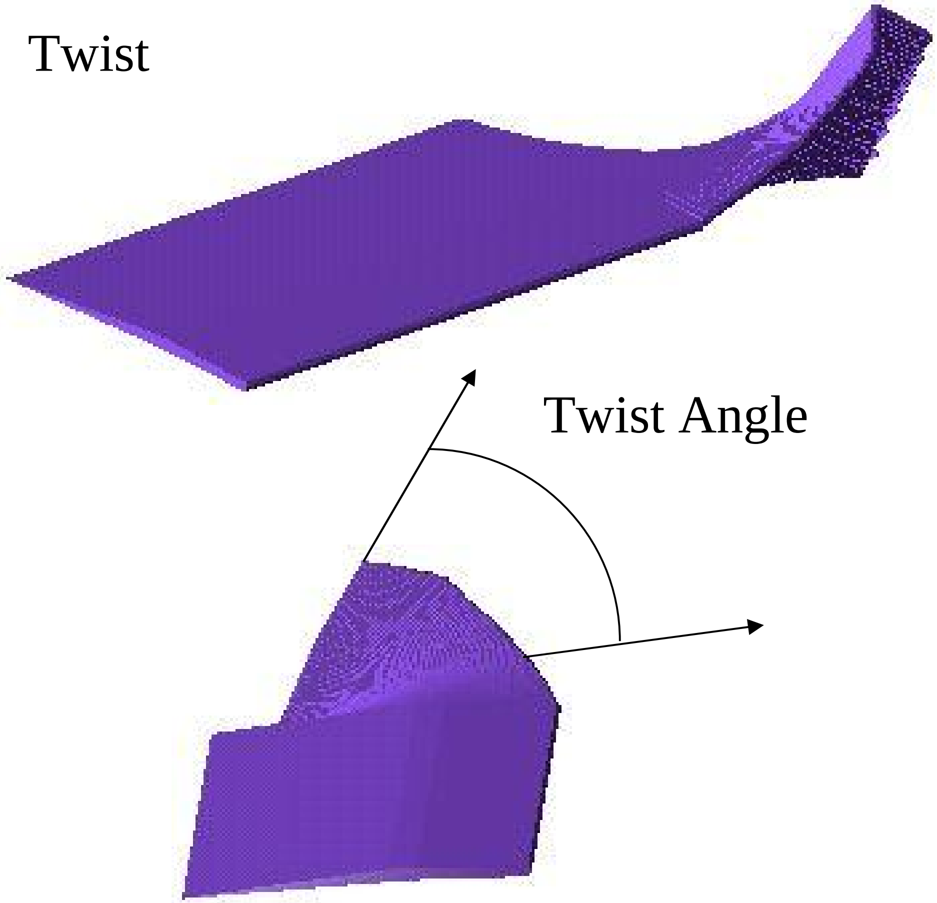
•Initial Chord distribution is based on the Pteranodon wing shape.

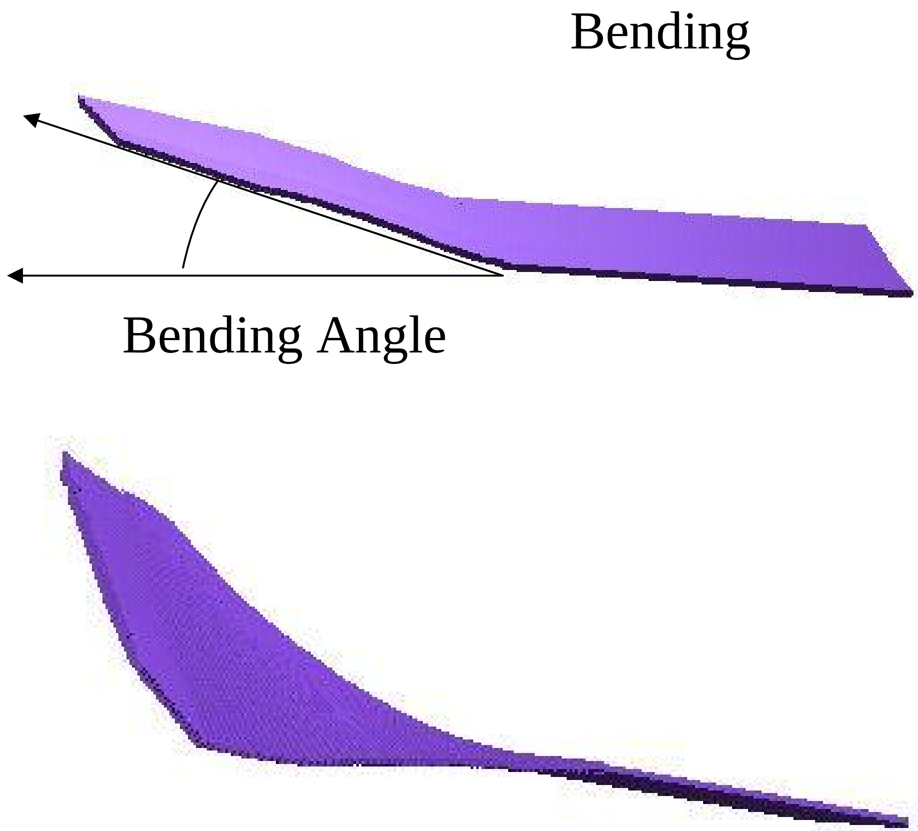
•Chord distribution will be optimized through CFD analysis for the design flight conditions of the SSA.



Determination of Optimum Wing Motion

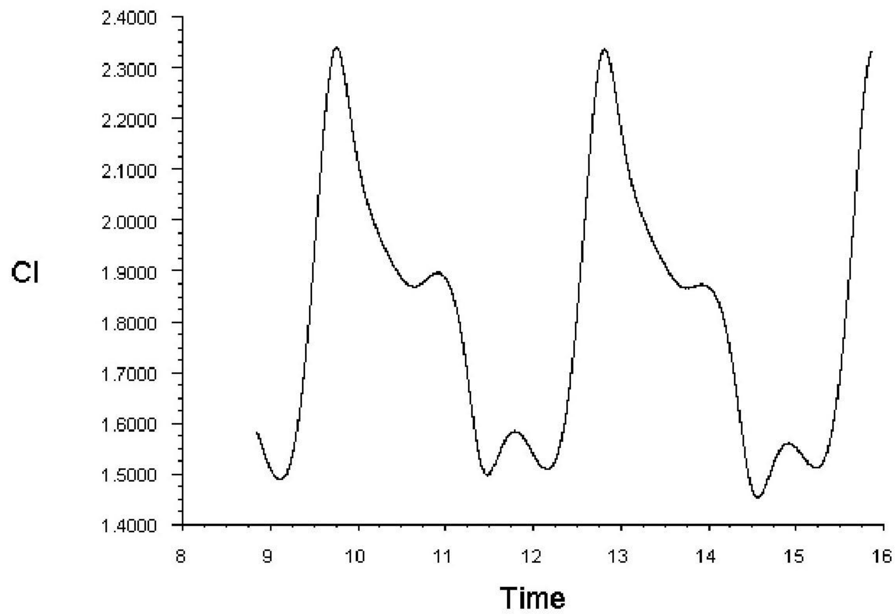
- There are two main wing motions that must be defined.
  - Flap Motion (bending)
  - Twist Motion
- CFD analysis is being used to examine the wing motion and determine flap motion that provides optimal performance

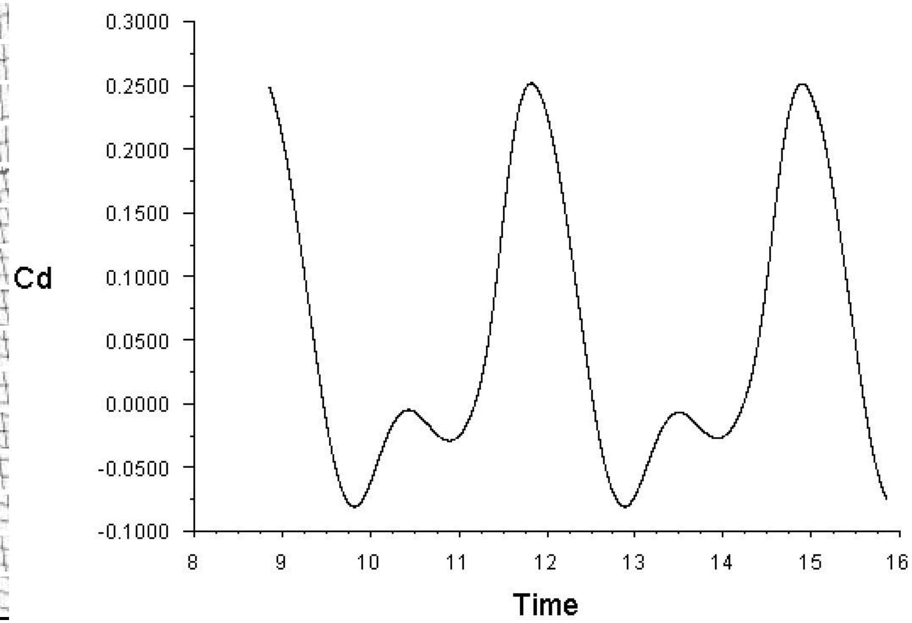




Aerodynamic & CFD Analysis Goals

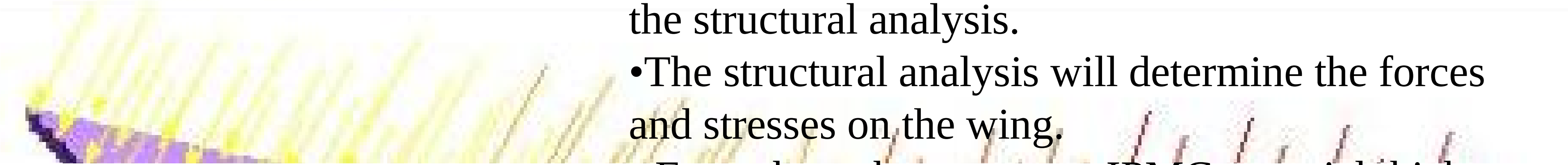
- The aerodynamic analysis is to provide a performance estimate (lift & drag) of the SSA under various operational conditions.
- Through an iterative process this analysis will be used to determine the optimum wing geometry and motion.
- Ultimately the CFD analysis is to provide a full 3D flow field over the SSA using the optimized wing geometry and motion for each potential operating location.
- This will validate the estimated SSA performance & provide a tool for further detailed evaluation of the concept.





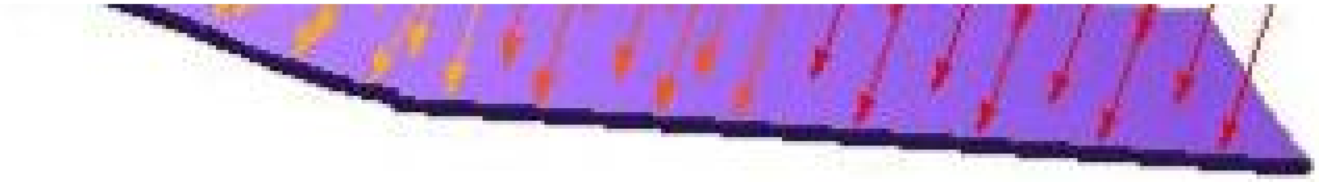
Structural Analysis & Design

Stresses Due to Motion



- The geometry and motion of the wing (established by the aerodynamic analysis) is used as the basis for the structural analysis.
- The structural analysis will determine the forces and stresses on the wing.
- From these the necessary IPMC material thickness will be determined.
- The thickness will vary from root to tip.
- The structural analysis is an iterative process with the aerodynamic analysis

Lift Generation ⟷ Wing Motion & Geometry ⟷ Structural Sizing & Loading



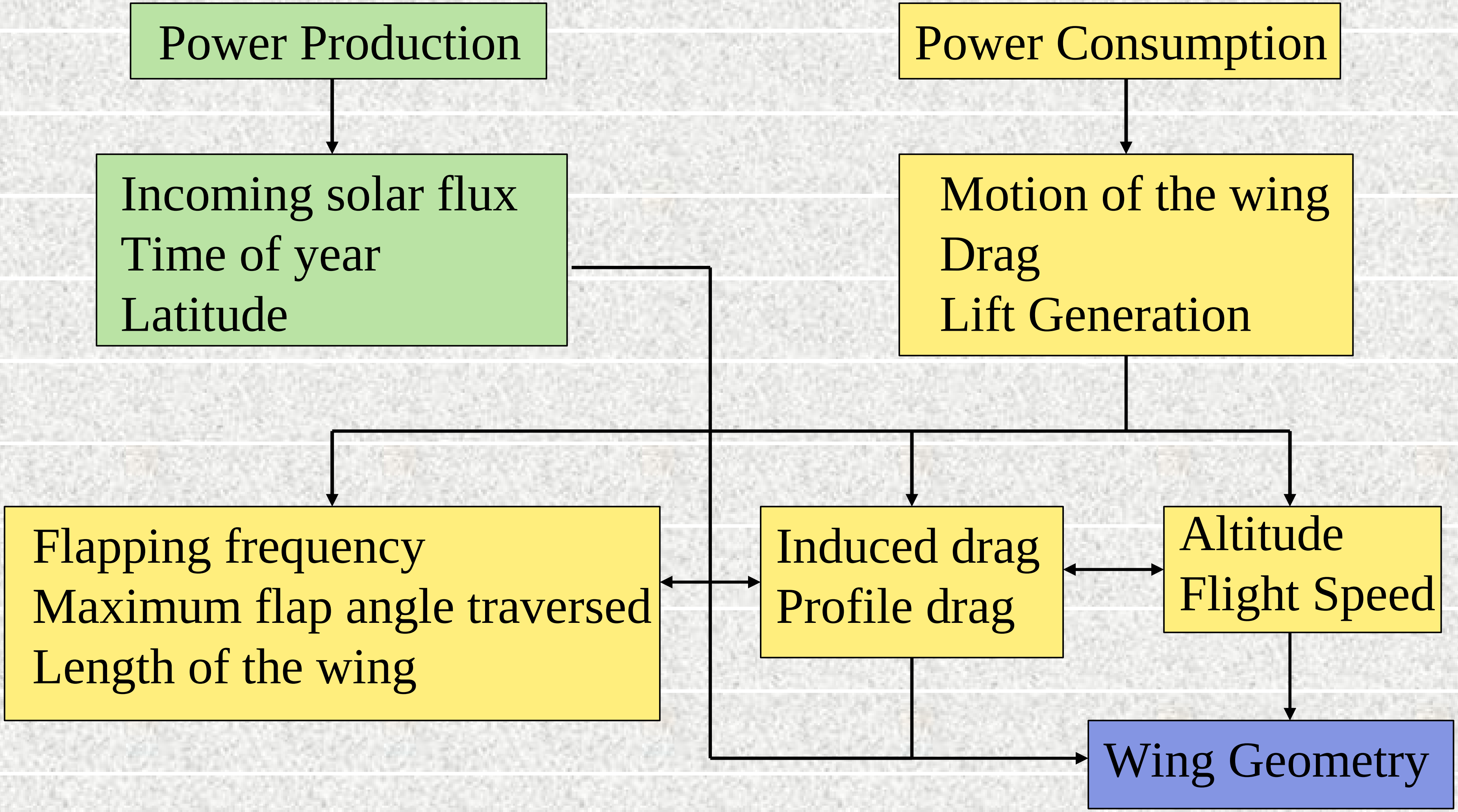
Environmental Considerations on the Structure

- The SSA must be capable of withstanding the environmental conditions at the various proposed operational locations.
- Resistance to corrosive atmospheric compounds (ex, sulfuric acid on Venus).
- Resistance to water evaporation from IPOC within arid environments.
- Low temperature operation.
- Erosive effects of dust (especially for Mars operation).

The selection and evaluation of coatings to resist these environmental effects is under way

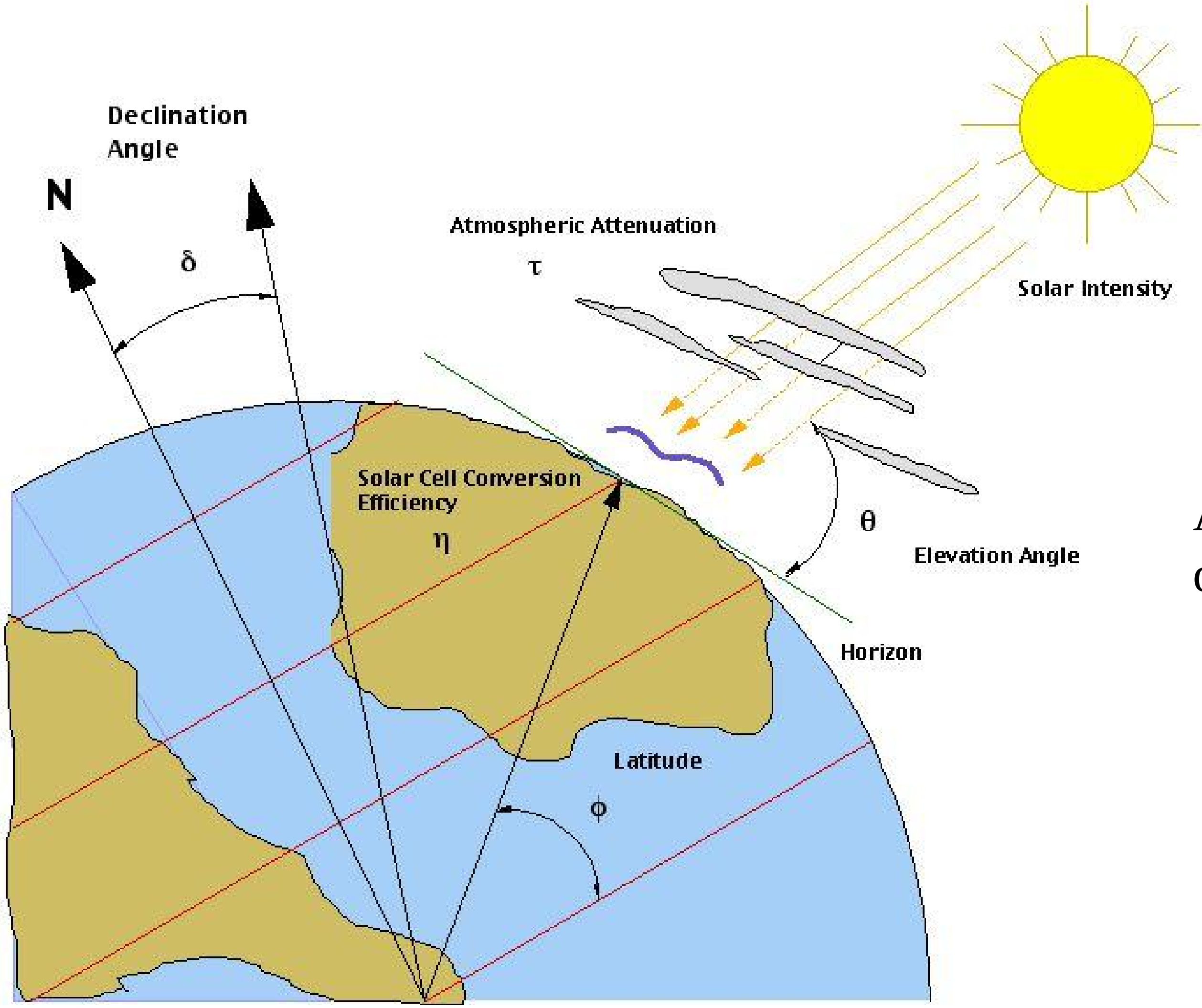
Sizing Analysis

An analysis was performed to determine the feasibility of the SSA concept and establish the range of operation on the planets of interest.



Power Production

The amount of power available to the aircraft is based on the Environmental conditions it is flying within



Output power will vary based on the

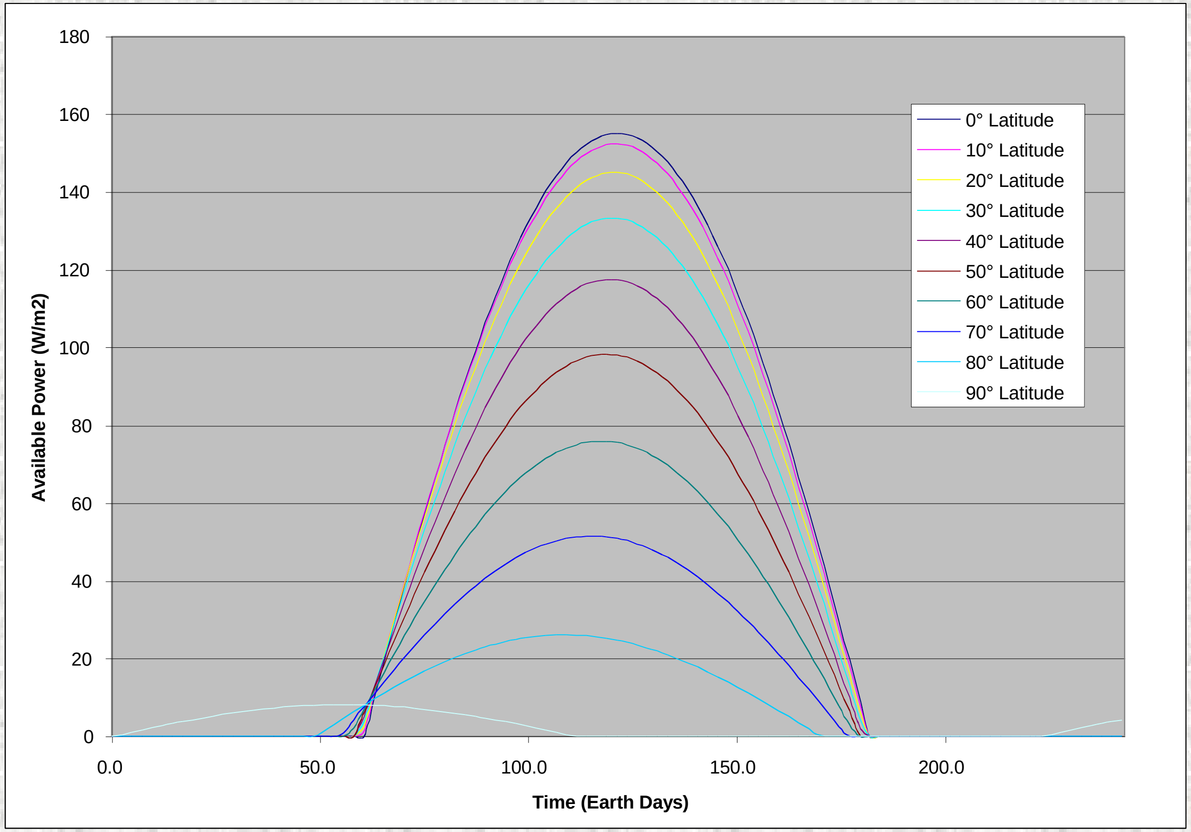
- Latitude of flight ( )
- Time of year (δ)
- Time of day (θ)

Available power also depends on the

- Atmosphere attenuation ( )
- Solar cell efficiency (η)

Power Production: Venus

There is no variation between daily and yearly power profiles because of the very long day length (equal to 263 Earth days) which is longer then the Venus year (equal to 244 Earth days)

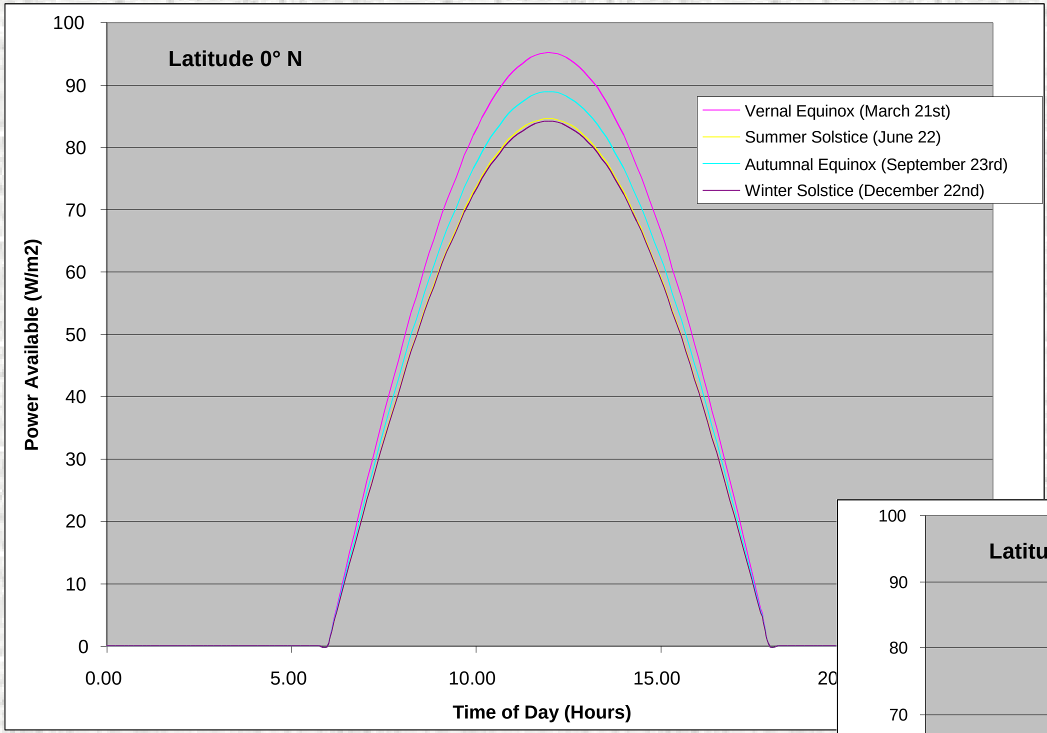


- Solar cell efficiency 10%
- Solar cell fill factor 80%
- Horizontal solar array
- Atmospheric Attenuation 25%
- Mean Solar Intensity above atmosphere 2620 W/m^2
- Longitude 0°
- Maximum declination angle 3°

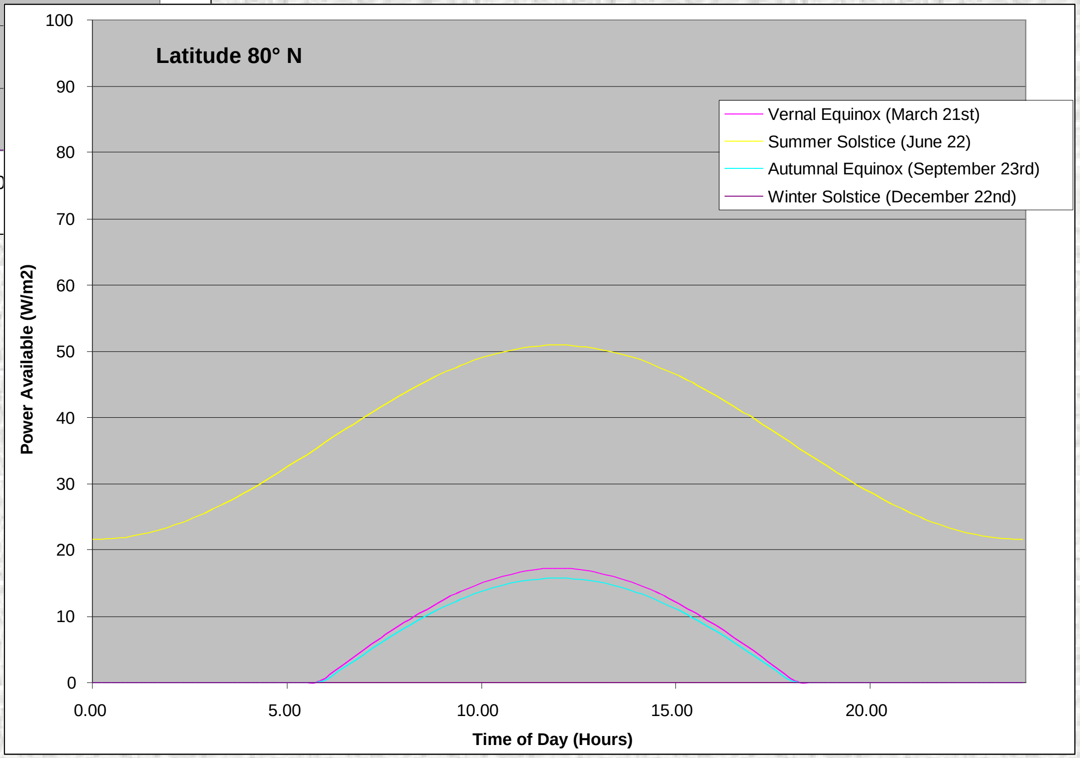
Available Power Throughout A Day (Earth Days)

Power Production: Earth

Available Power Throughout the Day (Hours)



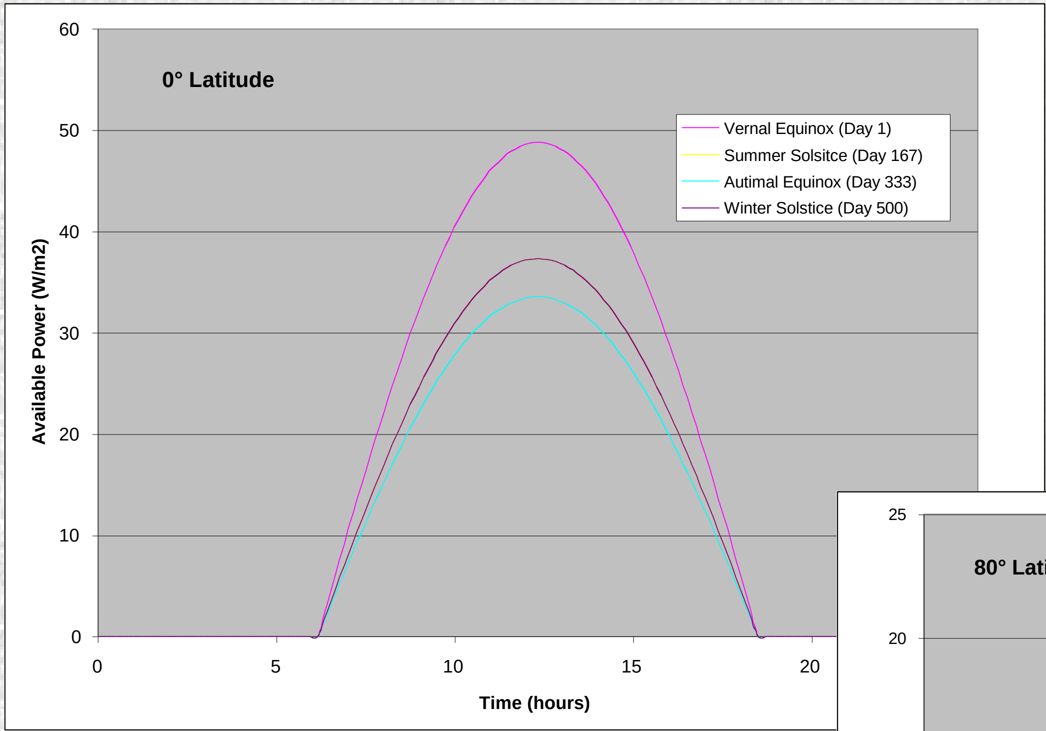
- Solar cell efficiency 10%
- Solar cell fill factor 80%
- Horizontal solar array
- Atmospheric Attenuation 15%



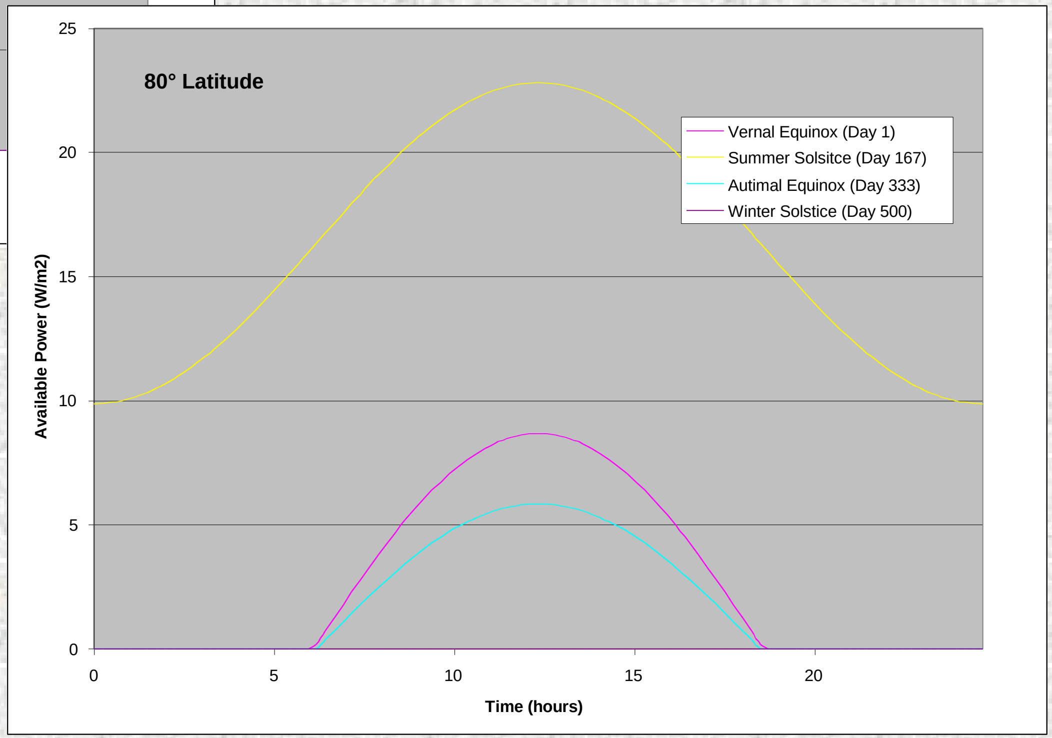
- Mean Solar Intensity above atmosphere 1353 W/m^2
- Longitude 0°
- Maximum declination angle 23.5°

Power Production: Mars

Available Power Throughout the Day (Hours)



- Solar cell efficiency 10%
- Solar cell fill factor 80%
- Horizontal solar array
- Atmospheric Attenuation 15%



- Mean Solar Intensity above atmosphere 590 W/m^2
- Longitude 0°
- Maximum declination angle 24°

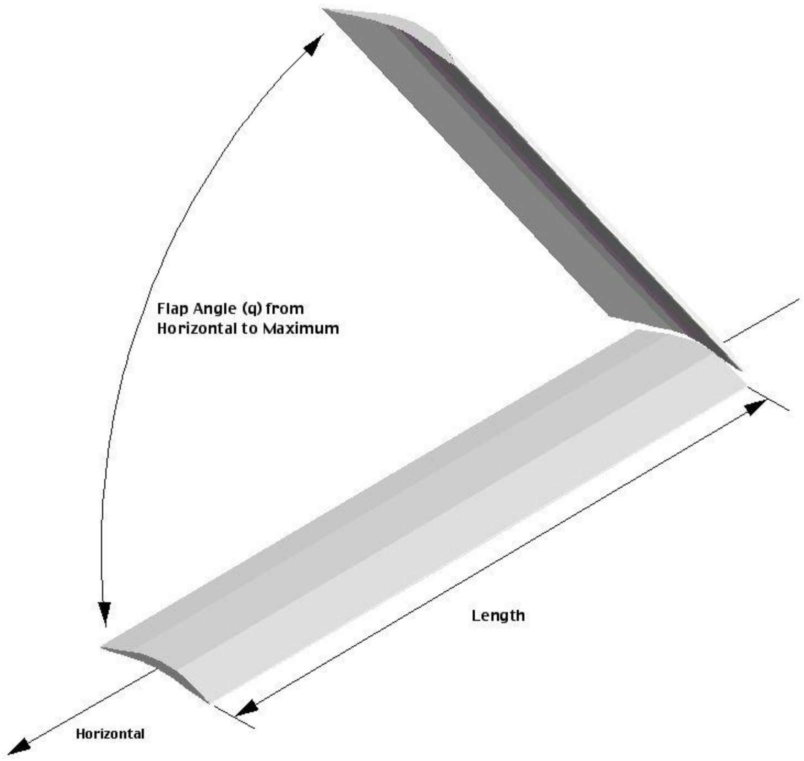
Power Production Throughout A Flap Cycle

The shorter the flap duration the greater the energy produced & however, the greater the power required

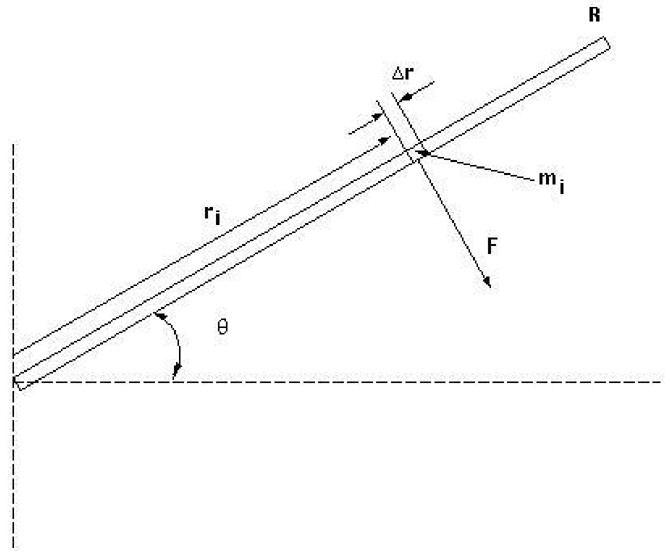
	Maximum Glide	Minimum Glide
Energy Available	12,658 J	11,961 J
Energy Required	12,658 J	2,439 J
Flap Duration	3.3 s	13.9 s
Glide Duration	10.6 s	0 s

Power Consumption due to Motion

Motion of the wing consists of a flapping rate and maximum angle traversed during the flap

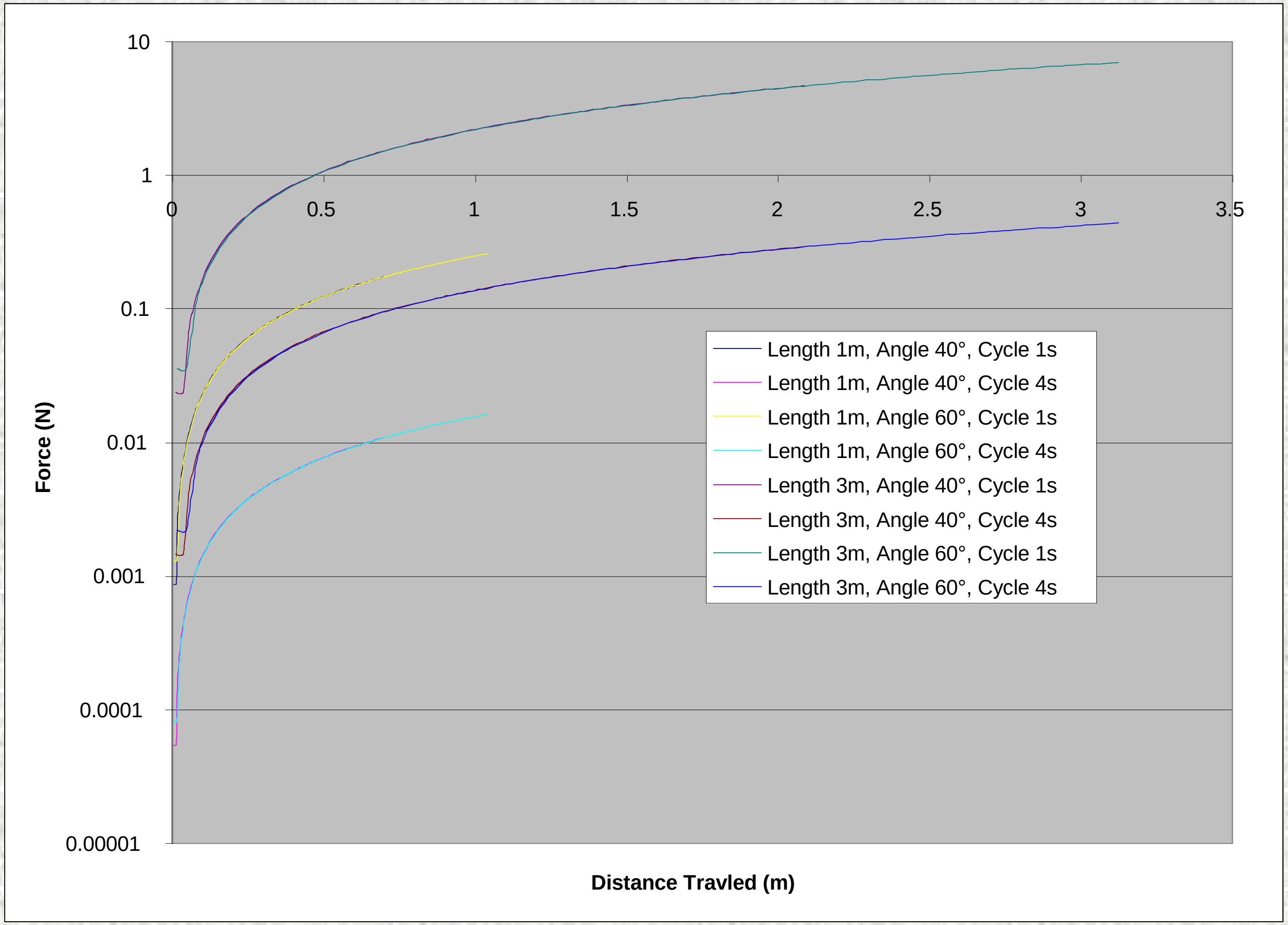


The forces generated by the wing motion are due to the acceleration and deceleration of the wing mass. These forces vary along the wing length



Wing Force Due to Motion

Force versus Distance Traveled for Various Wing Lengths, Maximum Flap Angles and Flap Frequencies

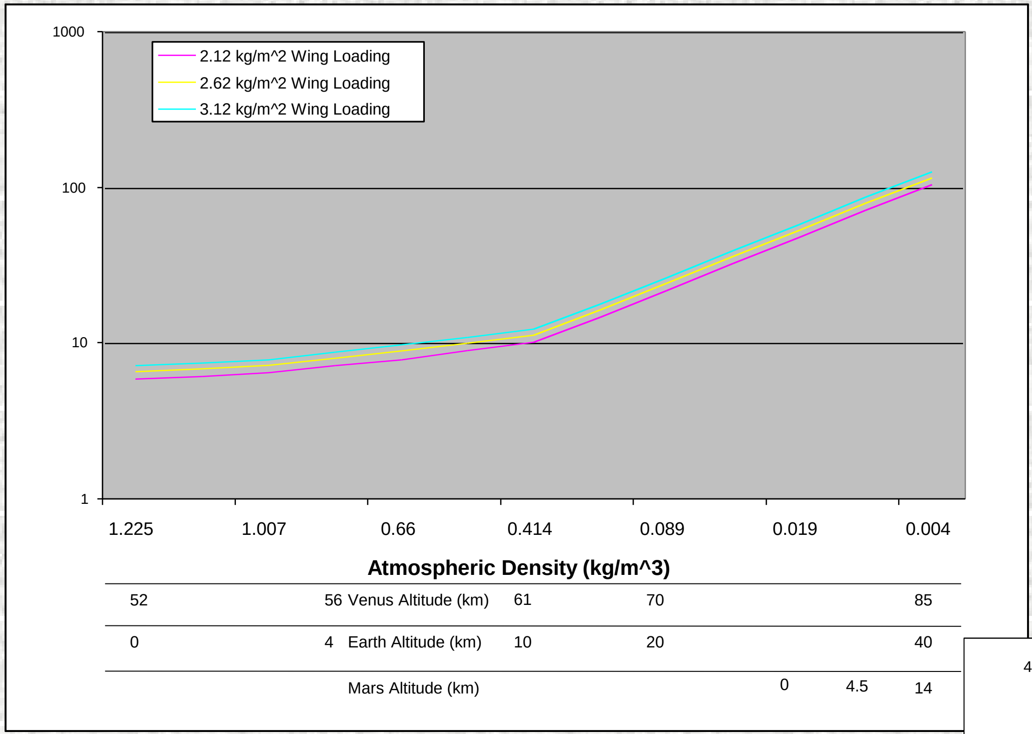


The power required to move the wing is the area under the force vs distance traveled curve.

The distance traveled varies along the wing length to a maximum at the tip.

Power consumption can be reduced by tapering the wing so there is less mass at the tip. Thereby reducing the force needed for motion.

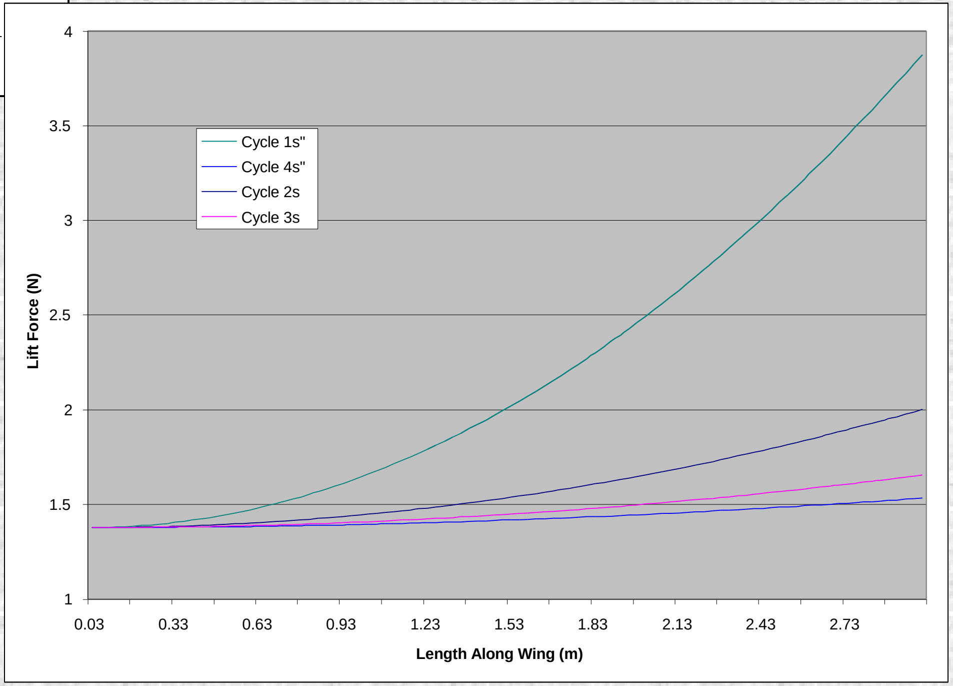
Drag Due to Lift and Velocity



The aerodynamic drag is due to the generation of lift and the movement of the aircraft through the atmosphere

$$D_f = \sum_0^i \frac{1}{2} V_i^2 (c_f 2S + c_d S)$$

The drag is dependent on the flight velocity which in turn sets the lifting capacity and the lift to drag characteristics of the airfoil.



Analysis Method

The energy consumed during the flap has to equal the energy collected during the total flap and glide cycle.

Inputs
Flapping Frequency
Flap Angle
Aircraft Size
Altitude

Power Available

Lift Generated

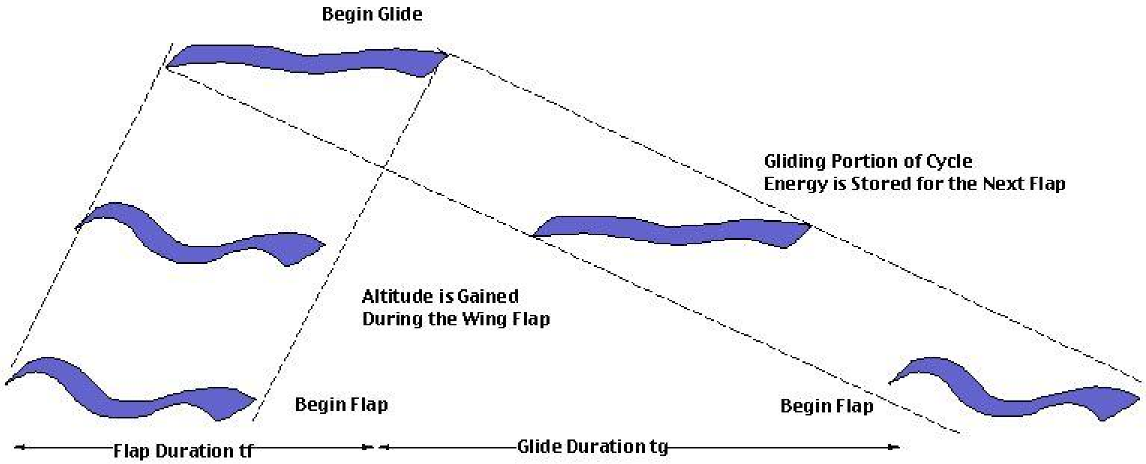
Power Consumed (Motion & Drag)

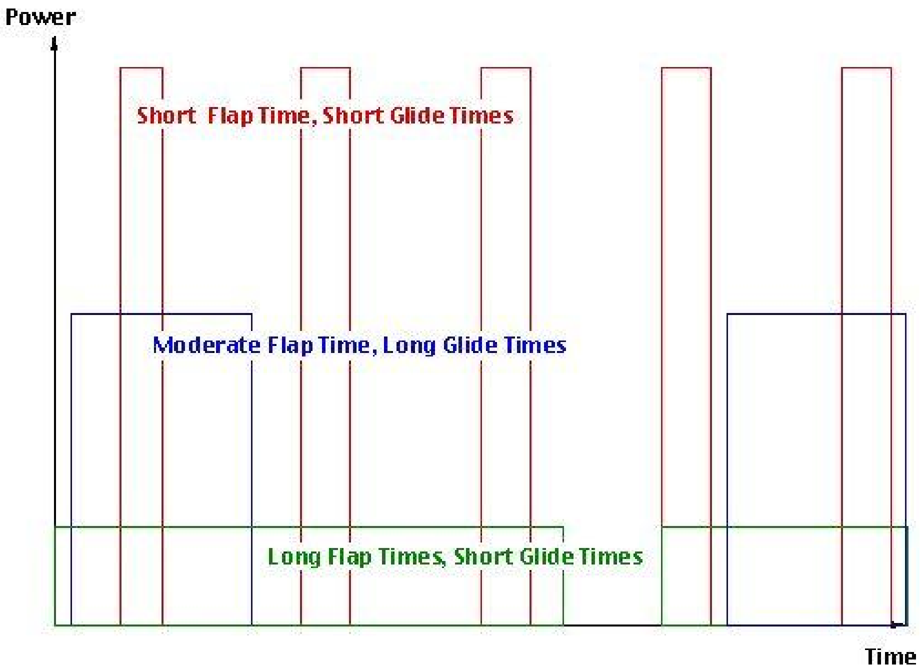
Flight Speed
Flap to Glide Ratio

- The analysis was an iterative process
- For a given set of inputs the flight speed and flap to glide ratio would be calculated.
- If no solution existed then certain inputs would be varied until a solution was found.

Operational Scheme

- The longer the flap cycle the larger the amount of energy that can be collected for the cycle energy balance.
- The aircraft will glide for extended periods of time and flap its wings periodically to regain altitude and increase forward speed.





The ratio of glide time to flap time will depend on the available power, power consumption and flight conditions.

The analysis was performed to determine the optimal glide to flap ratio for a give aircraft configuration under a specific flight condition

Aircraft Sizing

The initial feasibility study was performed to determine the capabilities of the aircraft under the environmental conditions of the planets of interest.

This initial analysis was based on the following assumptions

Wing Loading	3.12 kg/m^2
Aspect Ratio	8
Wing Friction Coefficient	0.008
Maximum Flap Angle	60° Parabolic Distribution
Solar Cell Efficiency	10%
Solar Cell Specific Mass	0.12 kg/m^2
Battery Specific Mass	0.75 kg/m^2
IPMC Specific Mass	2.00 kg/m^2
Payload Specific Mass	0.25 kg/m^2

Potential flight altitude ranges investigated in the analysis for each of the planets of interest

Venus	53 km to 82 km
Earth	1 km to 35 km
Mars	1 km to 7 km

Effect of Latitude

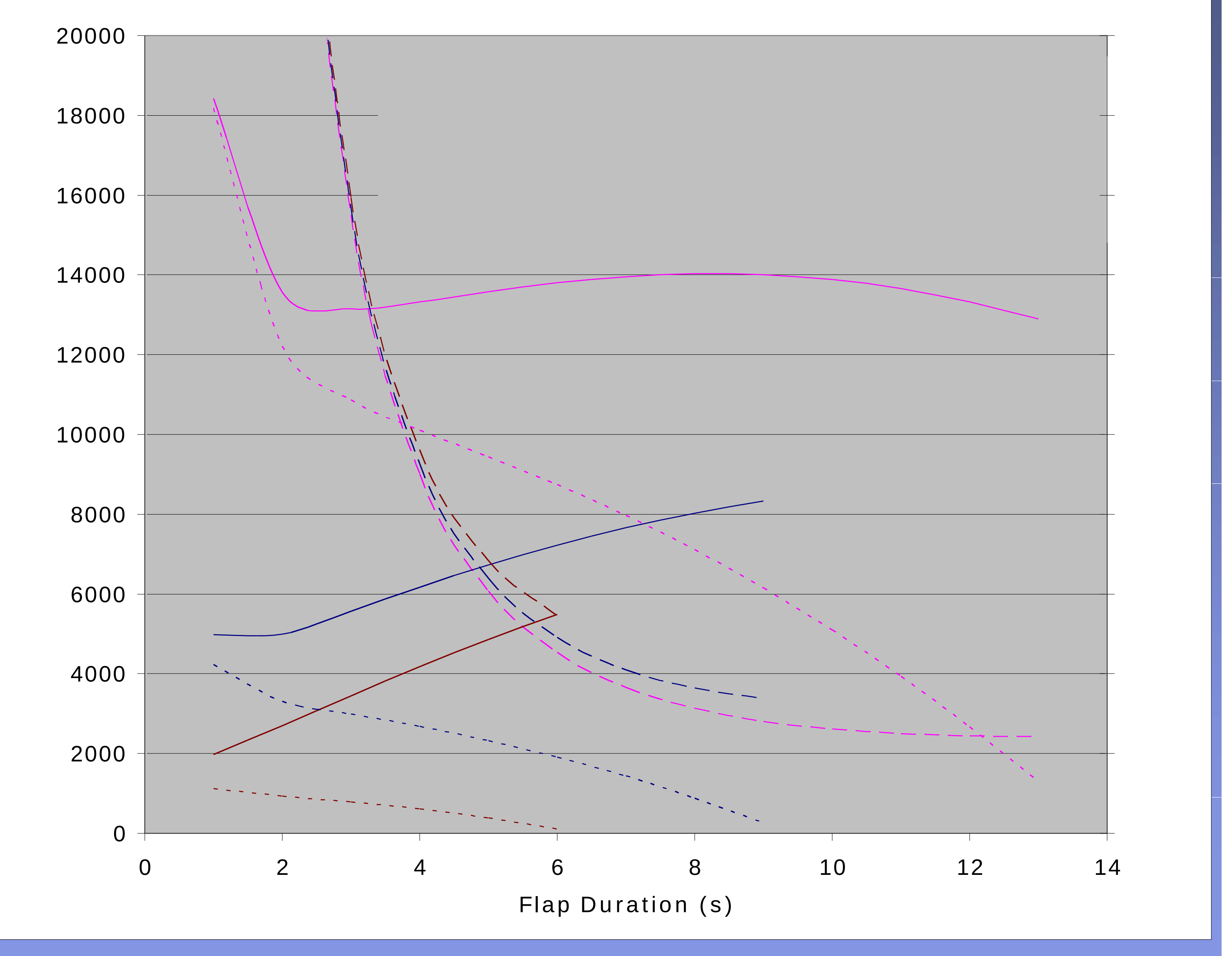
For Flight on Earth at 15 km Altitude on March 21st with a 10m wingspan

- As latitude increases the available energy decreases.
- The energy required decreased with increasing flap duration, until the glide duration equals zero.
- Energy available increases as the cycle time (flap duration + glide duration) increases.
- The minimum power required occurs when the glide duration goes to zero. This is because the required flap duration time increases at a faster rate then the decrease in glide duration.

Effect of Altitude

For Flight on Earth at 45°N Latitude on March 21st with a 10m wingspan

- Energy required varies slightly with increasing altitude.
- As altitude increases the maximum flap duration decreases. Shorter more frequent flaps are needed to compensate for the lower density air.
- Energy available is reduced as altitude increases due to the shorter flap cycles.



Effect of Time of the Year

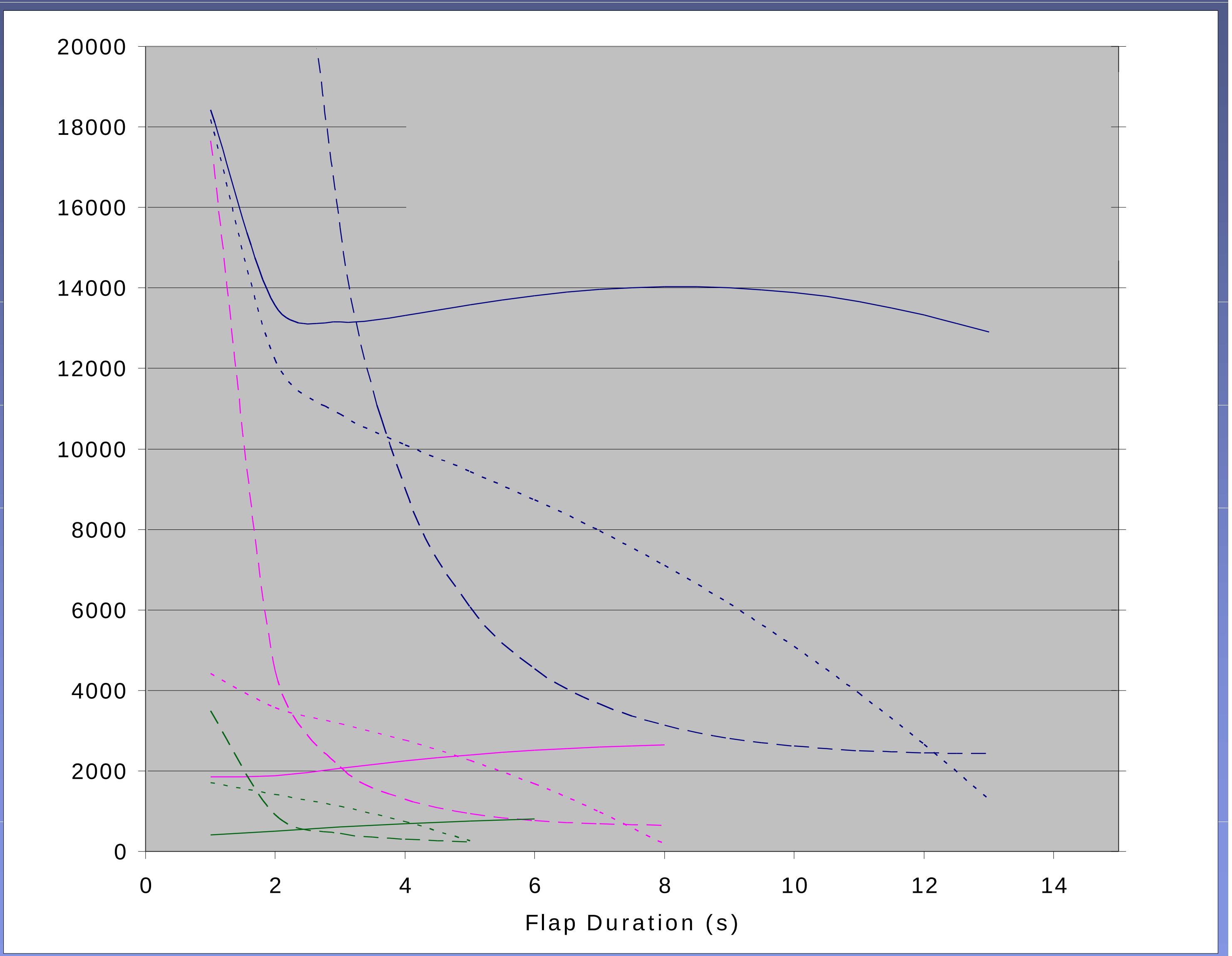
For Flight on Earth at 45°N Latitude at 15 km Altitude with a 10m wingspan

- The available energy decreases in the winter months and increased during the summer due to seasonal effects.

Effect of Aircraft Size

For Flight on Earth at 45°N Latitude, Altitude of 15 km on March 21st

- The aircraft scales with size by increasing the flap duration.
- Larger aircraft require more energy per flap but also produce much more energy.
- At a given altitude the larger the aircraft the larger the flap durations can be and therefore the more efficient the aircraft is.



Maximum Achievable Altitude

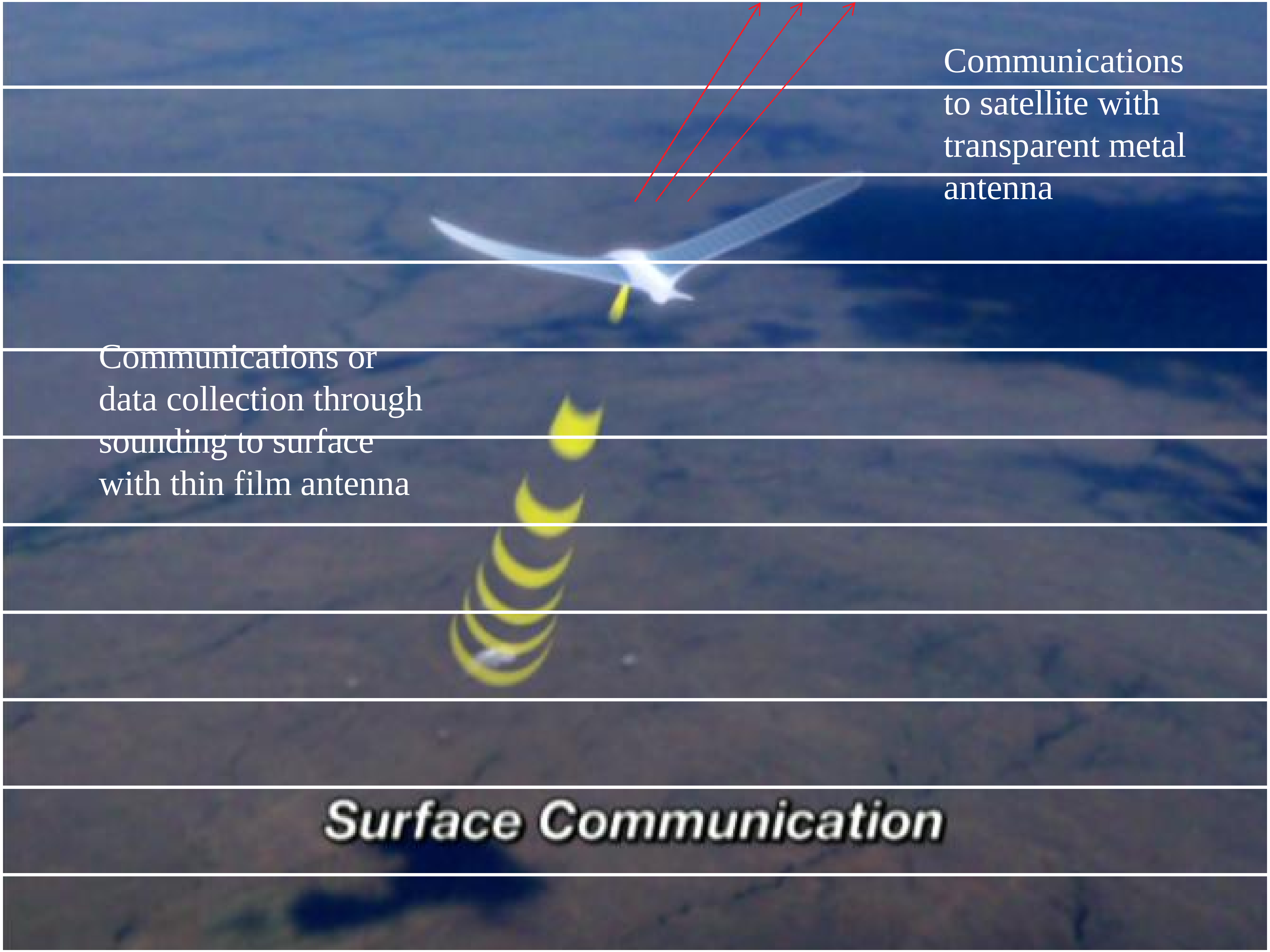
For Flight on Earth at 45°N Latitude,

- Curves show flight at the maximum efficiency when the glide duration is zero.
- As the aircraft size increases the maximum altitude increases but this is a diminishing

Communications System

•Getting data & information to and from the SSA is a critical function.
•The unique configuration of the SSA & its thin light flexible structure pose a unique challenge for the communications system.

Issue	Options	Design & Selection Factors
Antenna Type	Wire Flexible Thin Film Planar	SSA Layout FlexibilityRequiremen Data Transfer Capability
Antenna Placement	Trailing Integrated Coating	SSA Layout Mass
Data Requirement	UWB Fixed Band (ka, radio etc.)	Power Environment Payload & Mission


Communications to satellite with transparent metal antenna
Communications or data collection through sounding to surface with thin film antenna
Surface Communication

Thin Film Antenna

•The thin film antenna holds the most promise for use on the SSA
•It is thin lightweight and flexible which fits well with the SSA requirements
•The antenna could be mounted over the complete bottom side of the SSA. This would provide a large receiving and transmitting area.

•Bottom side mounting would enable transmission to & from the surface for both communications & science data collection.
•There is the potential for making this type of antenna transparent which would all it to be mounted on top of the solar array for data transfer to an orbiting spacecraft.
•Ultimately, if the thin film antenna can meet the SSA mission needs, there is the potential of having the antenna constructed as another material layer on the SSA which would provide a truly integrated composite vehicle.

Mission Analysis

- Utilizing the SSA capabilities established from the performance & communications analysis & vehicle design work, an evaluation of the potential mission the SSA may be capable of carrying out will be made.
  - Critical factors will be flight duration, flight altitude, payload capacity, payload power availability& data transfer capability.
  - From these various types of science data gathering & observing equipment will be assessed.
- The mission assessments will be performed for all three potential planets of operation.
- Both individual & multiple aircraft operations will be considered.
- For multiple aircraft missions, a fleet of SSAs can be considered which could either perform a unique task or provide an infrastructure such as a communications network.
- Specific aspects of the missions are also being considered these include:
  - Stowage while in space transit (for Venus and Mars missions)
  - Deployment
  - Navigation
  - Altitude Control
  - Landing

Science & Payload

Science & other equipment will be evaluated for use on the SSA. This evaluation will take into consideration the instruments mass, volume, power requirements and operational concerns such as vibration as well as the potential for miniaturization.

Potential science & data gathering includes:

- Camera, high resolution and contex
- Atmospheric measurements: temperature, pressure etc.
- Magnetic field measurments.
- Communications relay transmitter / receiver
- Atmospheric sounding with various frequencies (dependent on the capabilities of the communications system)
- Beacon

In addition to specific payloads, the systems on board the SSA will be evaluated to determine if any dual use potential exists. For example the communications antenna may be used to send receive signals at various frequencies in order to collect data in a sounding fashion.

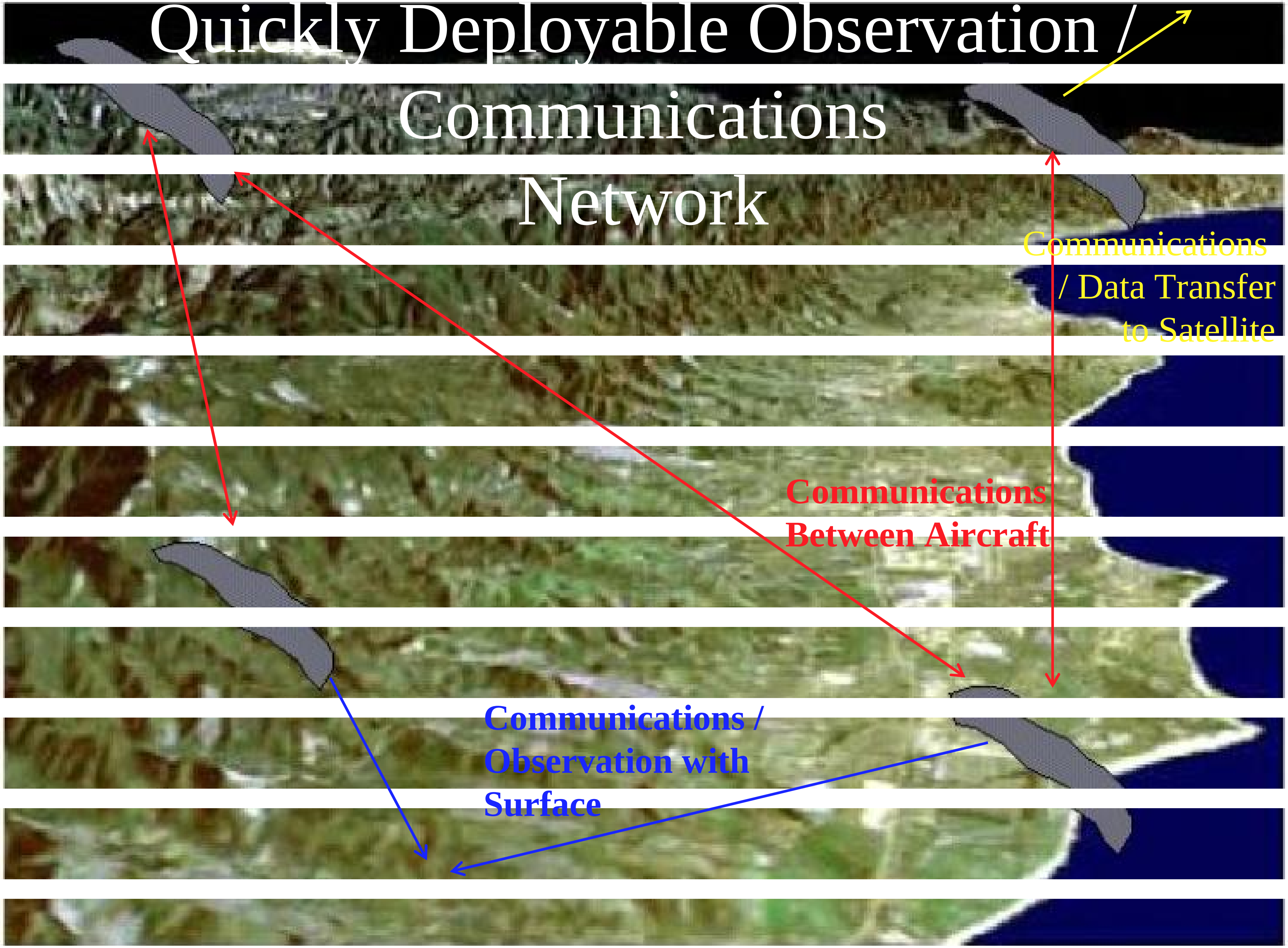
Science: High Resolution Imagery

- Detailed images can be taken on a regional scale at high resolution
- Vertical structures (canyon, mountain) can be imaged at various angles
- Imagery can be used for survalence, mapping or geological characterization of the planet.

Science: Atmospheric Sampling & Analysis

- Examine the Atmosphere Both Vertically &
- Sample Atmospheric Trace Gases
  - Oxidizing Species
  - Oxidizing Agents and Absence of Organics in Martina
- Investigation of Dust within the Atmosphere and
  - Sample Long Lived Airborne Dust in the Atmosphere

Quickly Deployable Observation / Communications Network



SSA Mission Animation